# A VALIDATION ASSESSMENT OF THE STORM

## AIR-TO-AIR PROTOTYPE ALGORITHM

THESIS

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AFIT/GOA/ENS/00M-06

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PROTOTYPE ALGORITHM

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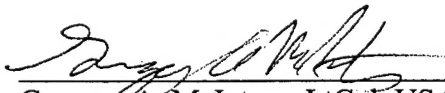
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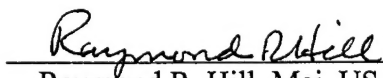APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

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# A VALIDATION ASSESSMENT OF THE STORM AIR-TO-AIR PROTOTYPE ALGORITHM

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# Table of Contents

# List of Figures

# List of Tables

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# Abstract

A validation assessment of the new STORM air-to-air prototype algorithm is accomplished using structural and output validation techniques. In the structural validation phase, the algorithms, code, and assumptions are evaluated to determine if the implementation of the model will match the intent of the designers. The components of the algorithm are compared to its predecessor, THUNDER, to evaluate if the prototype improves upon the weaknesses of THUNDER. In the output validation phase, the results of the model are evaluated to determine the extent to which the implementation of the model matches expected outcomes. Sensitivity analysis is presented to provide insight into the responsiveness of the algorithm to changes in aircraft performance. A two-level half-fraction factorial design with seven factors is used to determine the most significant factors.

# A VALIDATION ASSESSMENT OF THE STORM AIR-TO-AIR PROTOTYPE ALGORITHM

## 1. Introduction

### 1.1 Combat Modeling Tools

Campaign modeling is the art and science of representing the full theater of warfare and the inter-relationships between actors inside, and, sometimes, outside the theater. Similarly, campaign analysis is the art and science of quantifying the relative merits of the components of the campaign in order to derive insight into their performance or about the outcome of a campaign itself. The objective of campaign analysis is to provide information to senior decision-makers who must answer the "so what" questions involving force structures, operational concepts, and military capabilities. The campaign analyst seeks to measure the utility and effectiveness of military assets, forces, capabilities, and operational concepts. The models that are used for campaign analysis must be concerned with breadth before depth of coverage of the campaign environment. A model that represents many areas is more helpful than a model that simulates one area really well. At the campaign level, there is a high interest and necessity to model such things as air-to-air weapons usage and attrition at a reasonable level of fidelity.

THUNDER is the Air Force's most comprehensive theater-level analytical campaign simulation to date. It was designed to explore issues of utility and

effectiveness involving the large-scale application of air and space power in a joint warfighting context. THUNDER is typically employed in applications that explore issues of readiness, compare alternative courses of action, facilitate senior staff training through wargaming, and provide insights into future military strategies and evolving operational concepts. The air war model uses a discrete event, time-stepped stochastic simulation whereas the ground war model uses a discrete event, time stepped deterministic simulation. The air-to-air engagement algorithms used in THUNDER are based on research performed by George S. Fishman and Louis R. Moore while at the University of North Carolina [8:8].

The Synthetic Theater Operations Research Model (STORM) will be replacing THUNDER as the primary theater level model. STORM will be campaign in its scope and level of detail but also "...broadens its purview beyond that of THUNDER, by providing more robust representations of space, communications, and C4ISR assets and interactions" [29:7].

STORM will support in-depth analysis of the campaign-level contributions of air and space power. It is designed as a multi-sided, stochastic computer simulation of military operations across the air, space, land, and maritime domain to examine issues involving the utility and effectiveness of air and space power in a theater-level, joint warfighting context. STORM originated out of the movement of the Joint world toward a new generation of models. The Joint community developed the Joint Simulation System (JSIMS) for training and the Joint Warfare System (JWARS) for analysis. To support and complement these tools, each service is developing its own next-generation, High

Level Architecture (HLA)-compliant training and analysis simulations. The National Air and Space [Warfare] Model (NASM) was developed by the Air Force to address training requirements. The National Air and Space [Warfare] Model/Analytic, Next Generation (NASM/AN) program's objective is the design and implementation of an analytical simulation of theater-scale model in a joint warfighting context. STORM is the centerpiece of this effort.

STORM will support senior decision makers across the acquisition, policy, and operations communities. It will be able to provide the required information with a high degree of responsiveness in terms of analytical focus and turn-around time for results. Typical uses are [30:2]:

- Analyses of readiness, modernization, sustainability, and force structure issues.

- Alternative Course of Action (ACA) studies.

- Assessments of evolving capabilities, alternative strategies, and potential operational concepts.

- Wargaming to facilitate senior staff education and training.

STORM attempts to strike a proper balance between functionality, credibility, and compliance. Functionality ensures the model is usable by the analyst through user interfaces, transparency, available data, *etc*. Credibility ensures that the fidelity of the simulation accurately represents reality. Compliance ensures that the model is developed with close regard to current and future DoD modeling and simulation initiatives. STORM fits near the top of the familiar hierarchical pyramid of the Air Force suite of

3

models shown in Figure 1. Notice that as one moves up the pyramid, there is more abstraction, larger scope, and more data sources [5:3].

As entity detail decreases, the actions of the entities become more abstract. The scope refers to the length of time and geography span. Also, as the scope increases, the numbers and variety of entities within the simulation increases.

The air-to-air portion of the STORM model has been designed to improve upon 14 years of THUNDER's development and modification. THUNDER's air-to-air model has been useful but "...suffers from limiting assumptions that oversimplify the problem" [29:7]. The air-to-air portion is the focus of this research.
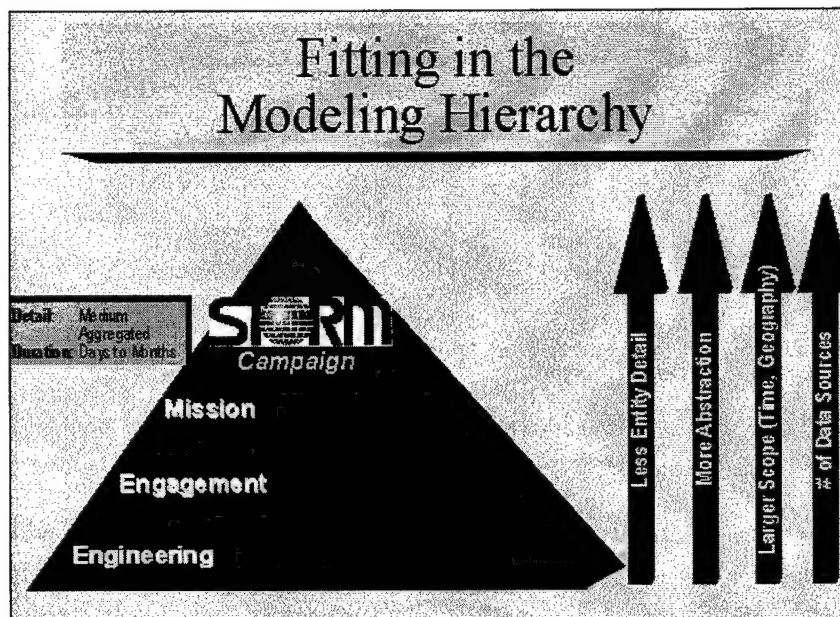


**Figure 1.  Air Force Modeling Hierarchy**

A THUNDER user must input the number and type of weapons fired (by configuration, by mission) for any air-to-air engagement. The user-input shots tend to cause the more numerous aircraft to overshoot at the lesser aircraft [29:7]. Regarding THUNDER, Denhard [8:79] identifies four stated criticisms of the air-to-air submodel:

- Problems with the single shot probability of kill and range advantage issues,

- Number of weapons fired per engagement by an aircraft is the same for all air-to-air engagements regardless of type of opponent aircraft faced,

- Multiple weapon salvo is always modeled as a SHOOT-SHOOT firing doctrine while the USAF typically employs a SHOOT-LOOK-SHOOT firing doctrine, and

- THUNDER does not allow for aircraft to disengage before weapons release.

The developers of STORM have selected a heuristic and event-oriented approach to model air-to-air engagements. This approach was chosen to improve transparency to users and is more suitable for medium aggregation needs. Other considered approaches were Markovian modeling (continuous and discrete), Event Occurrence Networks (proposed by Denhard for use with air-to-air engagement modeling [8]), and general process modeling.

Conceptually, STORM's air-to-air adjudicator is a mixture of the simple physical model and the interpolation approaches. The simple physical model provides a mechanism for anchoring the concepts of phases, volleys, and tactics. This statistical interpolation is designed to account for different types of engagements encountered during a campaign without burdening the user with vast data requirements. Air-to-air

combat is broken down into engagements, which are, in turn, sectioned into phases. Each phase is modeled as a series of volleys, with each volley representing an opportunity to make decisions such as "select target", "fire", "disengage", *etc.* [29:3].

An engagement occurs between opposing aircraft when certain conditions exist such as detection, cueing, proximity, and intent. The methodology calculates the weapon expenditures and aircraft attrition that result from an engagement. Time, distance, geometry, and tactics within the engagement are not explicitly modeled, and more detailed air-to-air models, such a BRAWLER, would be required to feed this information via input data. Upon conclusion of the engagement, the surviving aircraft return to the original flight to determine whether to continue or abort.

## 1.2   Typical Air-to-Air Engagements

Before continuing to look at the THUNDER and STORM models in detail. It may be beneficial to look at a "typical" air-to-air engagement from start to finish. This will provide a backdrop from which to form conclusions whether a model is acceptable.

The goal of all fighter tactics and maneuvering is to meet your aircraft firing requirements while frustrating that of your enemy. After the enemy aircraft has been acquired by radar, the friendly aircraft will try to position his aircraft by a series of maneuvers. These series of maneuvers are called tactics. In general, the actual maneuvers and tactics are dependent on the pilot's perception of the combat situation. Tactics have been developed to take advantage of the strengths of one weapon package and capitalize on the weaknesses of the opponent aircraft [8:155].

6

USAF aircraft typically engage opponent aircraft in two or four ship elements. Aircraft elements coordinate with each other concerning tactics and maneuvering and sharing of workload. When the engagement commences, the flights usually attempt to maintain only two ship elements. This size has been found to be most effective in maintaining mutual support while minimizing coordination problems [8:156].

A typical engagement starts with 40 nm or more separation between two opponent flight groups. Both aircraft are beyond visual range (BVR) of each other. An aircraft group must intercept the opponent aircraft through a series of tactics. These tactics are chosen based on the mission goals, rules of engagement, the geometry of the engagement, and so on.

For a tactical intercept there are six basic steps: detection, sorting, targeting, intercept, engage, and separate. The detection phase is the process of locating the enemy, or bandit, on your radar. This is limited by radar search volume that encompasses elevation, azimuth, and range. A pilot and his wingman normally have a search plan for locating the target identified by Ground Control Intercept (GGI). During the intercept portion of the air-to-air engagement, the on-board sensors provide the information regarding the opposing flight group. Sorting is the process of developing and updating a spatial layout of the opponent. It requires the flight to distinguish all potential targets. During this process, questions are asked about the state of the opponent aircraft such as, "How many threat aircraft are out there?", "What formation are they in?", and "What are they doing?". The friendly aircraft must decide which aircraft to attack and then become more specific in their intercept geometry. Targeting involves a flight taking a specific

target of responsibility. Intercept is the phase where you actually close on the opposing aircraft, trying to place the opposing aircraft in weapons envelope. This begins in the beyond visual range (BVR) range when missiles, such as the AIM-120, AMRAAM, are within the weapons envelope.

It should be understood that "...most air-to-air kills are against aircraft that have no idea that they are about to be fired upon. The further away an aircraft can fire a missile at an opponent and still have the missile be effective, the better" [8:162]. Therefore, this particularly should be modeled within the scope of a campaign model.

Next, in the engagement step, the element enters a visual fight with the opponent. Finally, separating is the decision process made in relation to the "escape window." The escape window represents the safe path out of the fight or separating from the fight. The following factors affect your position in the escape window [4]:

- Your range from the bandit,

- The energy of your aircraft relative to the opposing aircraft (the greater your energy, the more "open" your escape window), and

- Your combined angle-off [1] and aspect [2] with the bandit, with a head-on pass giving the best chance for an "open" escape window.

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[1] Angle-off is the difference between your aircraft and the opposing aircraft. For example, if the angle-off is 0 degrees, you would be on a parallel heading with the opposing aircraft. If the angle-off were 90 degrees, your fuselage would be perpendicular to the opposing aircraft.
[2] Aspect is the number of degrees measured from the tail of a target to your aircraft. This angle is important because, if you know this angle and range to target, you know his turning room from the target.

Perception is an important factor in the air environment. The task is to obtain as much tactical information as possible and analyze the information. An advantage can be gained by the passing of information from one aircraft flight to another. [8:156]

BVR weapons would be fired first given that the rules of engagement allow such action. The rules of engagement may require more information or visual identification. Within the 10nm range, the target has entered the within visual range (WVR) transition zone. At this point, each aircraft must decide whether they are in offensive, defensive, or neutral position relative to the opponent aircraft and whether they should attack, evade and reengage, or disengage. If deciding to attack, the pilot must rely on combat maneuvering tactics using infrared missiles and guns.

There are two types of tactical approaches in a WVR fight: the 'angles' fight and the 'energy' flight. In the angles approach, the pilot seeks to turn the aircraft for a position advantage in order to improve weapon firing capabilities. In the energy approach, the pilot seeks to gain an energy advantage by increasing or decreasing the energy of the aircraft (*e.g.* turning radius or altitude advantage) relative to the enemy aircraft without yielding a position advantage. Once there is an energy advantage, the pilot seeks to establish a position advantage. Both of these tactical theories depend on the type of weapon that is involved [24:99}.

"USAF tactics emphasize early shots, causing disruption, keeping airspeed up and avoiding getting drawn into a dogfight type engagement" [8:160]. A turning engagement is not desired since pilots would be fighting independently only giving mutual support by presence [8:160]. If it did come down to a turning engagement, basic flight maneuvers

(BFM) describe how aircraft maneuver against each other. BFM is usually grouped into the following three categories: Offensive, Defensive, and Neutral. With Offensive BFM, the goal is to shoot down the opponent in the minimum amount of time. It requires placing the enemy in the weapons envelope while denying the opponent an opportunity to launch. In Defensive BFM, the goal is to stay alive and separate from the opponent. Strategy centers around extending the engagement so the opponent is forced into an error. With Neutral BFM, this implies a null position/speed so that the pilot can either separate or try to gain an advantageous position.

## 1.3    Validation Issues

According to Department of Defense Directive 5000.59, validation is "...the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model." In this definition, accurate representation of the real world is qualified by the intended *use* of the model. The VV&A Recommended Practices Guide [11:8] states two prerequisites for cost-effective validation – intended use and a clear definition of the real world. If one does not know what he is modeling against, good and bad results can not be distinguished. The guide also gives a "lay man's" definition of validation when it states "...validation consists of comparing a prediction (from a simulation) with an observation (from the real world), and making a judgment about whether the result is good enough for application to your problem" [11:8].

Air Force Instruction 16-1001 breaks validation into two major components – structural validation (also called "conceptual validation" in other literature) and output

validation (also called "results validation"). Structural validation is the evaluation of the algorithms, code, and assumptions to determine if the implementation of the model will match the intent of the designers. Output validation is the evaluation of the results of the model to determine the extent to which the implementation of the model matches expected outcomes. Youngblood and Pace's [33:200] methods parallel that of the Air Force Instruction. They present two categories of validation methods – Conceptual Validation Methods (in general agreement with the "structural validation" mentioned previously) and Implementation (Results) Validation Methods. Conceptual validation is the review of assumptions, algorithms, modeling concepts, data availability, and architecture of the conceptual model to determine if the model is expected to provide an acceptable representation of the subject for the intended application. Results validation is the review process that compares model responses to known or expected behavior to determine that the responses are sufficiently accurate for intended uses [33:203].

Ketanni and Oral [15] present four major interdependent types of – formulational (structural), experimental (results), operational, and data validation. Formulational validation is mainly concerned with the "...degree of relevance of the assumptions and theories underlying the 'formal model' of the [real world event]" [15:224]. Experimental validation is concerned with the "...quality of solutions, the types of solutions, the nature of solution techniques, and the efficiency of solution procedures [15:224]." Data validation involves the "...sufficiency, accuracy, appropriateness, availability, maintainability, reliability, and cost of data" [15:222]. Operational validation refers to the usability, usefulness, timeliness, and cost of implementation of the model's recommended decision and is beyond the scope of this thesis.

This validation effort will utilize two methods, structural validation and results validation. First, during the structural validation, the algorithm for the air-to-air portion of STORM will be reviewed to determine if it has adequate fidelity and robustness to satisfy the intended use. This method will be used to establish the scientific basis for the algorithms by identifying any limitations as well as identifying any incorrect or restrictive assumptions. Important aspects of this method include: identifying the source upon which the algorithm is based, identifying higher-fidelity elements of the algorithm that will be lost because they are not processed by other elements of the M&S, and specifying the accuracy capability of the individual algorithm [33:8]. Second, this validation effort will utilize the results validation method. Comparisons will be made by comparing data points resulting from THUNDER. THUNDER provides a standard by which to compare but also a baseline from which to improve. Also, functional decomposition and testing will be used by decomposing the STORM air-to-air adjudicator into functional components. It provides a means of performing piecewise testing to determine if the M&S adequately represents the system.

The stated objectives by the developers of STORM are to "...represent attrition at least as well as THUNDER's current algorithm, improve the representation of munitions consumption, develop a methodology that will more readily calibrated with detailed engagement models (e.g. BRAWLER), and still maintains transparency for analysis in the field" [5:3]. This thesis effort will evaluate whether it has achieved these objectives and identify particular strengths or shortcomings.

## 1.4    Modeling and Validation of an Air-to-Air Algorithm

Air-to-air adjudication at the campaign level is a difficult proposition since no accredited approaches exist. Additionally, the problem itself is complex and lacks the data for the range of engagements normally encountered at the campaign-level. STORM attempts to address these uncertainties by providing a flexible aggregated representation of air-to-air combat. Validation will involve evaluating the tradeoffs between the degree of "data explosion" and transparency to the user versus improved fidelity of the model. Therefore, well-defined conceptual requirements are essential to ensure that an adjudicator is both useful and usable [29:9].

## 1.5    Statement of the Problem.

AFI 16-1001 lists independent third party validation as a viable technique for model validation. An independent validation of the STORM air-to-air algorithm is necessary to ensure that it represents air-to-air assets with an acceptable level of fidelity, given the tradeoffs discussed previously. It should at least model the air-to-air environment with the same level of fidelity as its predecessor, THUNDER. Furthermore, the development of STORM provides an opportunity to improve the weaknesses of THUNDER. This validation assessment will answer the questions, "Have the lessons learned from weaknesses in THUNDER been incorporated into the STORM algorithm?", "Does the STORM air-to-air adjudicator meet the objectives set by the developers?", and, finally, "Does the STORM air-to-air adjudicator adequately represent reality, keeping in mind its intended use?" This validation effort is confined to the use of the prototype

developed by S3I. Therefore, there may be issues that are addressed as deficiencies that may be incorporated outside of the prototype delivered.

## 1.6    Thesis Outline.

The approach of this thesis effort is to use validation tools and techniques to perform structural/conceptual model validation and output validation of the air-to-air algorithm within STORM. The model will be examined to determine whether or not it meets the objectives stated by the developers, namely: 1) ability to represent munitions consumption, 2) methodology calibrated with detailed engagement models, and 3) transparency to analysts in the field. This thesis is organized into chapters according to subject areas. Chapter 2 presents an overview of THUNDER with particular emphasis on the air-to-air modeling methodology. Chapter 3 presents an overview of STORM. Chapter 4 is a comparison of the THUNDER and STORM theoretical models and output. Chapter 5 presents sensitivity analysis of STORM input variables. Chapter 6 presents the conclusions of this thesis and recommendations for improving the STORM air-to-air adjudicator.

## 2.    THUNDER Overview

### 2.1    Introduction

THUNDER has been the Air Force's primary theater-level model for analysis since 1986. It is a two-sided, stochastic computer simulation of conventional air, land, and naval air warfare. THUNDER is used to evaluate force structures, conduct Analysis of Alternative (AOA) studies, develop strategies and tactics, and facilitate senior staff training through war-gaming. THUNDER will be replaced by STORM as the "Air Force's campaign analytic tool for acquisition and course-of-action analyses" to examine issues of air and space power [26:26]. This chapter presents a brief history, functional design, and previous validation efforts of THUNDER.

### 2.2    Background of THUNDER

THUNDER was developed from TAC WARRIOR, a theater level model used from the 1970's through the early 1980's. TAC WARRIOR proved difficult to use and to have underlying assumptions that were no longer valid to meet Air Force needs. Therefore, the Air Force Studies and Analyses Agency sponsored the development of THUNDER to correct the shortcomings. The model was first used operationally in 1986, as version 2.0. CACI, Inc. performed maintenance and upgrades from 1987 to 1993. Since 1993, both CACI, Inc. and System Simulation Solutions, Inc. (S3I) have maintained THUNDER. The most current version is THUNDER 6.6.

THUNDER is written in SIMSCRIPT II.5$^{®}$, a general-purpose programming language used for large, event simulations. The model consists of over 1,350 routines

combining for more than 300,000 lines of computer code and operates on the UNIX Operating System. THUNDER User Groups meet yearly to interact with THUNDER developers and fellow users. In addition, basic and advanced courses are offered for those interested. Currently, THUNDER User Groups consist of 35 distinct organizations in 42 separate sites in 5 nations. Some notable THUNDER users include:

- Air Force Studies and Analyses Agency (AFSAA)

- Air Force Wargaming Institute

- Boeing

- Joint Strike Fighter Program Office in Crystal City, VA

- Republic of Korea Air Force and

- Royal Air Force Air Warfare College

The three major assumptions identified for THUNDER for any campaign being studied are: 1.) The war is between two nation-state sized adversaries in a single theatre of operations, 2.) A defined boundary exists between opposing sides in the model, and 3.) The campaign can be expressed through a four-part process of Perception, Planning, Execution, and Adjudication.

Although THUNDER is primarily an air campaign model, many of the targets for air missions are generated by the ground war. The ground war cycle of THUNDER consists of four sub-functions: Command and unit definition, Initialization of the battlefield, Rear Area Transportation System, and Attrition of unit assets. The primary

measure of effectiveness (MOE) in the ground war is the movement of the Forward Line of Troops (FLOT).

Command and unit definition and initialization of the battlefield are scripted into the campaign scenario prior to the start. Ground forces consist of commands, which may have subordinate commands, and units. The unit is normally modeled at the division level consisting of any type combat unit. Both commands and units may possess air defenses (AD).

The ground war in THUNDER is based on the Center for Army Analysis's (CAA) Concepts Evaluation Model (CEM). As units engage in combat along the FLOT, combat is adjudicated by CAA's Attrition Calibration (ATCAL) model. Commands and units not engaged on the battlefield may move along the rear transportation network according to user input. The following eight orders control force structure and strategies in THUNDER: SUPERIOR, OBJECTIVE, EXPLOIT, FRONTAGE, DEPLOY.ON.CONTACT, SECTOR, ECHELON, and CAS.REQUEST.

As mentioned earlier, the ground war generates many of the targets used in the air war. These targets are generated by Intelligence, Surveillance and Reconnaissance (ISR). The level of ISR may be modeled at low, high, and very high resolutions. Ground truth of enemy positions and status is used in low resolution, while the perception of the enemy deteriorates with time unless updated with additional sensor sweeps in high and very high resolution modes. In high resolution mode, a side's intelligence on the enemy is based on the level of perception over zone-sector areas in the ISR grid and only aerial reconnaissance vehicles are modeled. Finally, the effects of varying levels of

reconnaissance coverage, timeliness, and sensor quality are accounted for in VERY.HIGH resolution mode and space surveillance is available.

An air/ISR grid and an associated air network support the modeling of air mission planning for air defense threat avoidance. An air grid is a collection of square area elements, each with the same size. In THUNDER, an air grid must have an even number of square elements in both the x and y coordinate directions. In addition, the air grid must cover the entire battlefield as specified by the user; however, the air grid may be larger and have different proportions than the defined battlefield. The user may assign certain squares in the air grid to be no-fly zones for red and/or blue aircraft. An air network is based on the air grid and is generated by THUNDER. To build the air network, the center points of each square area of the air grid are connected to each of its neighbors' center points.

THUNDER simulates three types of airbases: on-battlefield stationary airbases, off-battlefield stationary airbases, and moveable airbases. On-battlefield stationary airbases are geographically located within the battlefield grid specifications of THUNDER. Operational airbases have aircraft, aircraft maintenance, logistics resources, and of course, runways. Aircraft fly missions against the enemy from these bases and, since the airbases are stationary, an airbase may fall into the hands of the enemy.

Off-battlefield stationary airbases are positioned off the defined battlefield and are connected to the air network via connections to their closest square grid element on the air grid. Off-battlefield airbases have the same resources and capabilities as the on-battlefield airbases and may also be lost to the enemy.

18

Moveable airbases are carrier battle groups that model naval air operations. The major impact of declaring an airbase to be a carrier battle group is that the airbase can then change locations during the battle.

## 2.3   THUNDER Air War

THUNDER addresses all air warfare elements, including mission planning, base operations, base logistics, flight group assembly, flight group movement, *etc.* The air war in THUNDER is driven by air mission planning.

The purpose of air mission planning is to create Air Tasking Orders (ATOs). Aircraft squadron sorties are allocated to certain missions using a linear program to maximize squadron effectiveness in terms of capability, lethality, and mission priority. Once the squadrons have been allocated to specific missions they are assigned to enemy targets based on target priorities. Each target is generated based upon the perceived state of enemy resources (via ISR discussed earlier) and then given a target priority.

THUNDER creates flight groups once air mission planning produces the ATOs. Each flight group consists of various flights, one being a primary flight with the same mission as the flight group and the other flights acting in support of the group mission. THUNDER allows aircraft flights to take-off from different airbases at pre-determined times and rendezvous at designated points on the air grid. This action allows for the formation of flight groups from individual flights.

THUNDER also models air-to-air refueling (AAR). At the beginning of the air planning stage, THUNDER determines the total amount of air refueling capacity for each

air command. When a flight leaves an airbase and heads for its group rendezvous point, its flight path is not modified to account for having to refuel. The user may, however, provide an appropriate aircraft time delay at this stage of the operation to account for air refueling.

Once the flight groups are assembled, the groups proceed to their destinations as defined in their ATOs. Aircraft flight paths may be generated with the goal of minimizing exposure time in enemy territory or with the goal of minimizing vulnerability based on the current state of enemy air defenses. Flights may then cross the FLOT to complete their missions. At any time, flights may incur losses from enemy ground or air threats.

An enemy flight group may be detected by either Ground Controlled Intercept (GCI) radar or by Airborne Early Warning (AEW) aircraft. The AEW detection range is a function of line of sight (LOS), AEW Radar Cross Section (RCS), and maximum AEW radar range.

THUNDER models 27 air missions, grouped according to mission objective in accordance with USAF doctrine. There are six main mission groups: air-to-ground, air-to-air missions, suppression of enemy air defense (SEAD), high value asset (HVA), and other missions. Table 1 provides a categorized list of the 27 different air missions modeled. Appendix A provides a detailed description of the "air-to-air" missions.

**Table 1. THUNDER Air Missions**

| Mission Objective | Mission |
|---|---|
| Air-to-ground | Close Air Support (CAS)<br>Battlefield Air Interdiction (BAI)<br>Air Interdiction (INT)<br>Offensive Counter-Air (OCA)<br>Strategic Targets Interdiction (STI) |
| Air-to-air | Barrier Combat Air Patrol (BARCAP)<br>Defensive Counter-Air (DCA)<br>Over-FLOT Defensive Counter-Air (ODCA)<br>High Value Asset Attack (HVAA)<br>Air-to-Air Escort (AIRESC)<br>Fighter Sweep (FSWP) |
| Suppression of Enemy Air Defenses (SEAD) | Direct SEAD (DSEAD)<br>Escort Suppression (ESUP)<br>Escort Jamming (EJAM)<br>Stand-off Suppression (SSUP)<br>Close-in Suppression (CSUP)<br>Stand-off Jamming (SJAM)<br>Close-in Jamming (CJAM) |
| High Value Asset (HVA) | Airborne Early Warning (AEW)<br>Reconnaissance (RECCE)<br>Stand-off Reconnaissance (SREC)<br>Airborne Refueling (AAR)<br>Offensive Theater Ballistic Missiles (OTBM)<br>Defensive Theater Ballistic Missiles (DTBM) |
| Other missions | Airlift (LIFT)<br>Hold aircraft in reserve (RESERVE)<br>Move aircraft to dispersal base if overrun (DISPERSE) |

## 2.4  THUNDER Air-to-Air Functional Design

The following assumptions of the air-to-air adjudicator have been listed in the draft Accreditation Support Package for THUNDER [2]:

- Given a successful sensing detection of enemy aircraft by on-station orbiting fighters or intercepting fighters at planned intercept point, an air-to-air event occurs.En-route aircraft do not initiate air-to-air engagements.

- The outcome of air-to-air engagement is determined probabilistically as a function of user-defined parameters for aircraft/weapon pairings and tactical rules of engagement.

- Outcomes are binary for aircraft (dead/alive).

- Weapon (missile and/or gun) expenditures and sequence of firing are pre-defined by user for each aircraft configuration.

- When an air-to-air event results in a kill, potential damage to other aircraft in the flight group is adjudicated in the Support Airbase Operations submodel.

If THUNDER is operating in high resolution mode, air-to-air combat is modeled in considerable detail. Flight groups are tracked individually and stochastic determinations are made as to whether defender and threat flight groups enter into the engagement. If an engagement is joined, then many-on-many engagement models characterize the air battle. Attrition rates for each flight in the flight group are determined and losses are incurred based on tactics, range advantages, and survival and kill probabilities for both the defending and attacking aircraft types. THUNDER sequentially aggregates the results of one-on-one combat engagement into flight group vs. flight group combat engagement for overall attrition values. The general process is depicted in Figure 2.

**One vs One Combat Engagement Calculations**

| Define aggregate weapon characteristics | Determine interceptor tactics |

Calculate RRAs (Release Range Advantages)

Compute shooter survivability

Compute engagement probabilities

Compute One vs. One attrition rate

| Loss Assessment | Normalize Attrition | Compute Attrition for Flt vs. Flt | Compute engagement probabilities |

**Flight Group Calculations**          **Flight vs. Flight Calculations**

**Figure 2. Aggregation of Calculations from One vs One to Flt Group**

The following sections contain a description of the air-to-air adjudication process in THUNDER. For a more detailed analysis with example, see [8:176-197]. The THUNDER air-to-air engagement model, adjudicates combat via three processes:

- A process that calculates a single shot probability of kill (*SSPK*) for each aircraft against possible opponent aircraft.

- A process that aggregates aircraft versus aircraft *SSPK* calculations to attrition rates for flight versus flight and flight group versus flight group levels.

- A process to assesses losses by drawing from a binomial distribution.

23

### 2.4.1 Single Shot Probability of Kill

Since a flight in THUNDER is composed of homogeneous aircraft, the *SSPK* calculation can be seen as a flight versus flight entity level process. The single shot probability of kill (*SSPK*) is calculated as follows for each aircraft versus opponent aircraft combination (each of these variables will be explained in the following sections):

$$SSPK = ENG * LCH * PK \qquad\qquad (1)$$

where,

$ENG$ = the probability of engaging the opponent aircraft,

$LCH$ = the probability of firing a weapon at the opponent aircraft, and

$PK$ = the probability of killing an opponent aircraft given a weapon firing.

### 2.4.2 Probability of Engaging the Opponent Aircraft (*ENG*)

In THUNDER, an engagement will always occur if the intercepting flight group detects the target flight group. The probability of engaging the opponent aircraft (*ENG*) is based on the product of two factors: the general engagement probability, $ENG_{AEW}$, (based on whether the flight group is under airborne early warning (AEW) or ground-based control) and a modification component reflecting the flight group tactics. $ENG_{AEW}$ is dependent on the opponent's platform.

The intercepting flight group can then employ one of three tactics:

- Engage the target flight group's escort aircraft only.

- Engage the target flight group's non-escort aircraft only.

- Engage the non-escort aircraft with percentage $a$ and escort aircraft with a percentage $1 - a$.

In THUNDER, $a$ is referred to as the allocation ratio. This value is determined by calculating a series of Lanchester difference equations and an allocation measure of effectiveness (See [8] for a detailed description of this calculation).

In similar manner, the target flight group can employ one of three tactics:

- All escorts split from the target flight group to engage the intercepting flight group,

- All escorts stay with the target flight group, or

- A percentage $m$ stay with the target flight group and a percentage $1 - m$ split from the target flight group to engage the intercepting flight group.

The $m$ variable is known as the "mutual defender ratio" (a user-input value).

Given these tactics described above, the equations for the probability of engaging the opponent (*ENG*) at the aircraft (or flight) level for the target flights can be formed. They are:

$$ENG = ENG_{AEW} * a \tag{2}$$

for the intercepting flight engaging non-escorts,

$$ENG = ENG_{AEW} * [(1 - a)] \tag{3}$$

for the intercepting flights engaging escorts,

$$ENG = ENG_{AEW} * [(1 - a) * (1 - m) + m] \tag{4}$$

for target flight escorts engaging the intercepting flight, and

$$ENG = ENG_{AEW} * [a * (1 - m) + m] \qquad (5)$$

for target flight non-escorts engaging the intercepting flight.

### 2.4.3 Probability of Firing a Weapon at an Opponent Aircraft (*LCH*)

The next variable in the Single Shot Probability of Kill calculation is the probability of firing a weapon at an opponent aircraft (*LCH*). It is based on an aggregation of the individual weapons carried by the aircraft and not for each individual aircraft type. The *LCH* calculation is a combination of the following variables:

- Relative Range Advantage - the number of a weapon type that can be fired before an opponent shoots his weapon type,

- Opponent's Probability of Engagement,

- Number of friendly and opponent's aircraft in each flight,

- Opponent's Probability of Kill, and

- Opponent's "Force Multiplier".

In order to fire, one of the following three scenarios must exist for the firing aircraft:

- The firing aircraft has an overall relative range advantage and can fire without threat of being killed by the opponent (*i.e.* the firing aircraft can fire at the opponent before the opponent fires a weapon at it),

26

- The firing aircraft does not have an overall relative range advantage, but the opponent aircraft cannot engage the firing aircraft, or

- The firing aircraft does not have an overall range advantage, but the firing aircraft survives a specified number of firings of an aggregate weapon by the opponent.

Each of these has a probability of occurrence that is added together to determine *LCH*. Let each of the probabilities for the above scenarios be designated by $LCH_i$ , i =1, 2, 3 respectively. Thus, $LCH = LCH_1 + LCH_2 + LCH_3$

For the first scenario, $LCH_1$ can best be understood by an example. Consider an F-15C versus a MIG-29. The F-15C is carrying AIM-120s and AIM-9s. The MIG-29 is carrying AA-10s and AA-8s. There are four possible combinations of first weapons fired between these two aircraft:

(1) AIM-120 versus AA-10,

(2) AIM-120 versus AA-8,

(3) AIM-9 versus AA-10, or

(4) AIM-9 versus AA-8.

In combinations 1 and 2, the F-15C has a range advantage over the MIG-29. In combination 3, the MIG-29 has a range advantage over the F-15C. In combination 4, neither side has a range advantage. Assuming that the weapon combinations are random, the F-15C will have a single range advantage over the MIG-29 50% of the time. The MIG-29 will have a single range advantage over the F-15C 25% of the time. Neither

aircraft will have a relative range advantage 25% of the time. Therefore, $LCH_1$ for the F-15C is 0.50. $LCH_1$ for the MIG-29 is 0.25.

The probability for scenario two, $LCH_2$, depends on the occurrence of two independent events. First is the firing aircraft does not have a relative range advantage on the opponent aircraft. The probability of this event is $1 - LCH_1$. Second, is that the opponent aircraft does not engage the firing aircraft. The probability of this event is $1 - ENG_{opponent}$. $LCH_2$ is then defined as:

$$LCH_2 = [1 - LCH_1] * [1 - ENG_{opponent}] \qquad (6)$$

The probability for scenario three, $LCH_3$, depends on the occurrence of the following three events. First, the firing aircraft does not have a relative range advantage on the opponent aircraft. Second, the opponent aircraft engages the firing aircraft with the probability of this event denoted by $ENG_{opponent}$. Lastly, the firing aircraft survives $n$ weapon firing from the opponent aircraft before his first weapon firing. The probability of this event is equal to:

$$(1 - PK)^n \qquad (7)$$

where $PK$ is the probability that the opponent aircraft kills the firing aircraft first. The $PK$ calculation will be described in the next section. The number of weapon firings, $n$, of the opponent aircraft is defined as:

$$n = FM \cdot \frac{n^A}{n^B} \qquad (8)$$

where,

$n^A$ = The number of opponent aircraft,

$n^B$ = The number of firing aircraft,

$$FM = \sum_i \sum_j \min([RRA, N \cdot FL_j^{opp}] \cdot FL_j^{opp} \cdot FL_i^{fac}) \text{ which is referred}$$

to as the force multiplier,

$RRA$ = Relative Range Advantage (the number of shots that the opponent can fire before your aircraft can fire),

$FL^{opp}$ = the fraction of launches for the opponent aircraft,

$FL^{fac}$ = the fraction of launches for the firing aircraft, and

$N$ = the number of weapon firings the opponent may take.

The concept of fractional launches can be explained by the following example. The aggregate weapon for a F-15C with an equal combination of AIM-120s and AIM-9s will have 50% of the characteristics of the AIM-120 and 50% of the characteristics of the AIM-9. These characteristics are called "fractional launches" in THUNDER. Assume, for another example, that a MIG-23 is firing 2 AA-7 missiles and 2 AA-2 missiles. The fractional launches of the AA-7 is 2/4 or 1/2, and the fractional launches of the AA-2 is also 2/4 or 1/2.

### 2.4.4  Probability of Killing an Opponent Aircraft (*PK*)

The user inputs the maximum number of launches per engagement. The engagement model assumes that an aircraft will always fire its maximum number of launches per engagement unless there is an insufficient number of weapons remaining.

The user determines the munitions fired in the $1^{st}$, $2^{nd}$, $3^{rd}$,..., $n^{th}$ engagement. As mentioned previously, all weapons fired in a single engagement by a single aircraft are aggregated into a composite weapon. The *PK* values in THUNDER are weapon versus platform dependent. To illustrate the *PK* calculation, assume you have MIG-29s (i = A) with an AA-10 (j = 1) and AA-8 (j = 2) and F-15Cs (i = B) with an AIM-120 (j = 1) and AIM-9 (j = 2). The composite probability of kill calculation is as follows:

$$PK^A = [FL^A_1 * PK^A_1] + [FL^A_2 * PK^A_2] \tag{9}$$

$$PK^B = [FL^B_1 * PK^B_1] + [FL^B_2 * PK^B_2] \tag{10}$$

where,

$\quad\quad\quad\quad FL^i_j$ = the fractional launches where i is the aircraft type and j is the

$\quad\quad\quad\quad\quad\quad$ weapon type,

$\quad\quad\quad\quad PK^i_j$ = the probability of kill for each aircraft/weapon combination.

### 2.4.5 Attrition Calculations

Next, the aircraft versus aircraft *SSPK* calculations are aggregated to determine attrition rates for flight versus flight and flight group versus flight group levels. Two sets of calculations are performed for the flight versus flight combinations. First, it calculates the attrition rate of a single opponent aircraft when engaged by the entire firing flight firing *one weapon each*. Second, it calculates the attrition of the single opponent aircraft when engaged by the entire firing flight group firing *all weapons*.

### 2.4.5.1 Firing Flight Firing *One Weapon Each*

Allowing for the possibility of multiple kills, the probability of *j* out of *i* firing aircraft killing an opponent aircraft is:

$$\binom{i}{j} \cdot (1 - SSPK)^{i-j} \cdot SSPK^{j} . \tag{11}$$

THUNDER assumes a weighted combination of the two firing flight engagement strategies based on the degree of command and control of the flight. First, if the firing flight has perfect command and control ($FCC = 1$), aircraft in the firing flight would divide themselves evenly over the aircraft in the opposing flight. Second, if there was no command and control ($FCC = 0$), aircraft in the firing flight would divide themselves randomly over the aircraft in the opponent flight. In the perfect command and control case ($FCC = 1$), the probabilities that $M$ and $M+1$ aircraft from the firing flight engage an aircraft from the opponent flight, $F_M$ and $F_{M+1}$ respectively, are:

$$F_{M+1} = REMAINDER\left(\frac{fac}{opp}\right) \tag{12}$$

$$F_M = 1 - F_{M+1} \tag{13}$$

where,

    $fac$ = number of firing aircraft, and

    $opp$ = number of targeted aircraft.

If there is no command and control ($FCC = 0$), the attacking aircraft randomly attack the defending aircraft. There would then be the possibility that some aircraft would not be attacked, while others would be attacked by several different aircraft. The probability that a defending aircraft will be attacked exactly $i$ times is:

$$G_i = \left(\frac{1}{opp}\right)^i \cdot \left(1 - \frac{1}{opp}\right)^{fac-i} \cdot \frac{fac!}{i! \cdot (fac - i)!} \qquad (14)$$

In reality, the command and control is between these two extremes of perfect command and control to complete lack of command and control. The probability that defending aircraft in a flight will be attacked exactly 0, 1, 2, ...$n$ times where $n$ is the number of aircraft in the attacking flight is:

$$P_i = F_i \cdot FCC + (1 - FCC) \cdot G_i \qquad (15)$$

where,

> $FCC$ = the flight command and control (average of the aircraft command and control values in the flight, a number between 0 and 1), and

> $F_i$ = from (12) and (13) discussed previously, the probability that $i$ aircraft from the firing flight engage an aircraft from the opponent flight under the strategy of "perfect" command and control.

Therefore, for each flight versus flight combination, the attrition rate of a single aircraft in the opponent flight entity when engaged by the entire firing flight, firing *one weapon each*, is:

$$ATTR = \sum_i P_i \sum_j \binom{i}{j} \cdot (1 - SSPK)^{i-j} \cdot SSPK^j \qquad (16)$$

### 2.4.5.2 Firing Flight Group Fires *All Weapons*

This calculation is similar to the entire flight firing one weapon each. Two probabilities are calculated:

- The probability that the opponent flight will be engaged $i$ times by the firing flight ($i = (1...m)$, where $m$ is the maximum number of weapon firings for the firing flight.

- The probability that in $k$ out of $i$ engagements, the firing flight kills and opponent aircraft.

Again, like the calculation of the firing of *one weapon each*, THUNDER assumes a weighted combination of two firing flight engagement strategies based on the degree of command and control of the flight. It is also based on the maximum number of launches any aircraft in the flight group can make (*max*). First, if the firing flight has perfect command and control ($FGCC = 1$), aircraft in the firing flight would divide themselves evenly over the aircraft in the opposing flight. Second, if there was no command and control ($FGCC = 0$), aircraft in the firing flight would divide themselves randomly over the aircraft in the opponent flight. In the perfect command and control case ($FGCC = 1$). A flight group's $FGCC$ value is assumed to be the average of all $FCC$ values of the flights in the flight group.

The two probabilities of engagement, $F_m$ and $F_{m+1}$, that must be computed for the flight group are:

$$F_{M+1}^{FG} = REMAINDER\left(\frac{fac}{opp}\right) \tag{17}$$

$$F_M^{FG} = 1 - F_{M+1} \tag{18}$$

where,

*fac* = number of firing aircraft, and

*opp* = number of targeted aircraft.

If there is no command and control (*FGCC* = 0), the attacking aircraft randomly attack the defending aircraft. The probability that a defending aircraft will be attacked exactly *i* times is:

$$G_i^{FG} = \left(\frac{1}{opp}\right)^i \cdot \left(1 - \frac{1}{opp}\right)^{fac-i} \cdot \frac{fac!}{i! \cdot (fac - i)!} \tag{19}$$

The probability that defending aircraft in a flight group will be attacked exactly 0, 1, 2, ...*n* times where *n* is the number of aircraft in the attacking flight group is:

$$P_j^{FG} = F_i^{FG} \cdot FGCC + (1 - FGCC) \cdot G_i^{FG} \tag{20}$$

where,

> *FGCC* = the flight group command and control (average of the aircraft command and control values in the flight group, a number between 0 and 1), and
>
> $F_i^{FG}$ = the probability that *i* aircraft from the firing flight group engage an aircraft from the opponent flight under the strategy of "perfect" command and control.

Therefore, for each firing flight group versus opponent flight combination, the attrition rate of a single aircraft in the opponent flight when engaged by the entire flight group firing *all available weapons* is:

34

$$ATTR^{FG} = \sum_i P_i^{FG} \sum_j \binom{i}{j} \cdot (1 - SSPK)^{i-j} \cdot SSPK^j \qquad (21)$$

In order to ensure that the flight group attrition rates are less than or equal to one, the attrition rates are "normalized." This is done by multiplying the attrition rate by the ratio of the total number of firings by the firing flight over the number of total firings by the flight group.

### 2.4.6 Engagement Losses Calculations

For each opponent flight, the number of aircraft lost is calculated using a draw from a binomial distribution. Because the actual aircraft losses cannot exceed the weapon firings, the actual amount of aircraft lost is the minimum of the binomial draw and the number of weapon firing designated for the firing flight. Similarly, because the number of aircraft losses cannot exceed the number of aircraft in the opponent flight, the total amount of opponent aircraft lost is the minimum of the sum of actual aircraft losses for each firing flight and the number of aircraft in the opponent flight. This assessment is performed for each flight in the opponent flight group.

### 2.5 THUNDER Current Validation Efforts

According to the Joint Accreditation Support Activity [2:4-4],

> As a campaign-level simulation of military operations, THUNDER is in a category of M&S for which output validation options are limited at best. The general consensus within the VV&A community is that the complexity of the known/addressed factors (the numbers and types of objects, processes and actions) and the extent of the unknown/unaddressed factors (behaviors, effects and interactions), when combined with lack of relevant field data, make output validation extremely difficult if not impossible in the theoretical sense.

THUNDER has been used in numerous studies by many different organizations. These studies are acknowledged by JASA to represent face validation that is "...significant, but generally not well-documented" [2:4-4]. In an effort to organize the studies that use THUNDER, a database has been developed to track the users and studies that benefited from THUNDER output. The intention was to support THUNDER's conceptual model. It is organized so that one can chose a submodel within THUNDER to see all of the studies that focused on that particular part of THUNDER.

Validity of input data is an important aspect of output validity. Documentation of data sources (*i.e.*, data pedigree) is being developed by some THUNDER users, *e.g.*, ASC/XR for the JSF program. This will facilitate subsequent data validation efforts. Another extensive validation effort was accomplished on the Intelligence, Surveillance, and Reconnaissance Module by Nelson, 1998 [21].

## 2.6   Summary

In addition to the features reviewed here, several improvements and modifications to THUNDER 6.6 have been recommended/proposed. For instance, in the air-to-air submodel, it has been requested that there be the ability to shoot through clouds or a certain altitude limitation, referred to as a "harddeck". This harddeck would be specified as an aircraft planning factor (by type aircraft, by time). It will put limitations on the aircraft's profile when it is required to deliver below ceiling. Also, this would allow for the real-world situation that air defense systems cannot acquire targets above weather ceiling.

THUNDER is a large and complex model that requires continual updating to improve its ability to model the warfare environment. Despite some limitations, the usefulness of the model cannot be overstated. There is much that can be learned from the analysis of various weapon types, capabilities, strategies, and, especially, their interactions. A strength of THUNDER is that the Air War is modeled at a slightly higher resolution than is available from other resources, while the automatic ATO generator saves the user time to input the orders.

Despite its usefulness, many believe the time has come for the next-generation campaign model to be developed. STORM will be used to capitalize on THUNDER's strengths and improve its limitations. In particular, THUNDER's air-to-air adjudicator will be redesigned to model attrition as accurately as THUNDER but improve such things as munitions consumption.

## 3.   Review of the STORM Air-to-Air Algorithm

### 3.1   Introduction

The National Air and Space [Warfare] Model is the parent model of the NASM/AN Program.  The main focus of NASM is on training, but the Operational Requirements Document requires a robust analytical capability to measure the contributions of air and space power at the campaign level.  Therefore, STORM is the centerpiece effort to design the next generation analytical simulation of theater-scale military operations.  System Simulations Solutions (S3I) is the primary model developer and system integrator.

The developers of STORM have selected a heuristic and event-oriented approach to modeling air-to-air engagements.  This approach was chosen in order to make the process more transparent to users and suitable for medium aggregation needs.  STORM attempts to address the uncertainties of various air-to-air situations by providing a flexible aggregated representation of air-to-air combat.

### 3.2   STORM Overview

Regarding model development, the STORM initial approach is to cover a wide spectrum of missions and representation with a limited level of detail.  As development continues, specific mission areas will be added as appropriate.  "The candidates for increased detail include those missions most critical to the proper representation of air and space power and missions most understood by operators and subject matter experts [26:12]."

STORM's core model will be an event-driven, stochastic process in which entities from multiple sides will interact in air, land, sea, and space environments. It is being written in the C++ programming language and will be compliant with DoD high level architecture (HLA) requirements.

There are five top-level object classes in STORM: Environment, C2 Managers, Interaction Managers, Assets, and Intelligence Managers. The Environment is the foundation of STORM and serves as the game board for the entities. It provides weather and terrain effects for the rest of the model's objects. Weather is divided into forecasted and actual weather. Forecasted weather is used in the planning process while actual weather affects detection, attrition and weapon delivery events. Terrain is the medium upon which surface entities move and affects how the C2 Managers plan for entity movements. Terrain also affects weapon lethality, direct vs. indirect fire potential, terrain masking of sensors, *etc.* The C2 Managers provide computer control of the planning processes for the simulation entities. An analyst must "teach" the computer C2 Manager to make decisions that adapt to the warfare simulation. The C2 Manager's plans, in turn, control the core behavior of each entity in STORM. Interaction Managers are the "referees" for STORM and adjudicate any interactions between entities. In order to facilitate simulation development, modification, and enhance model transparency, STORM has separated interactions into their own objects (*e.g.* Space, Air, Ground, *etc.*). Assets are explicit representations of the entities within the simulation. These assets are divided into object sub-classes which are given individual characteristics through input data. These assets are aggregated and disaggregated dynamically to apply the appropriate amount of detail while meeting runtime constraints. The capstone of STORM, the

Intelligence Managers, control the perception of the entities within the simulation (*i.e.* the ground truth). The Intelligence Manager logs and updates information as it is perceived. It also reconciles the degree of overlap and redundancy as multiple observations are made of numerous entities. It combines all observations of all entities into a single picture of the battlespace. "This perception employs the 'best' observation of each 'known' entity to develop an information base to support the C2 Managers' planning functions and the reactions of individual Assets during the simulation" [26].

Following USAF doctrine, STORM missions are defined by their objectives rather than the type of aircraft accomplishing the mission. Appendix A contains a detailed description of the mission types. Table 2 lists STORM's planned air-to-air mission capabilities and their ties to Air Force doctrine [30:59].

### 3.3    STORM Air-to-Air Methodology

Certain aspects of air-to-air combat are modeled outside of the air-to-air adjudicator. For instance, the initial STORM air-to-air prototype assumes that an engagement *can* occur. The steps that lead up to an engagement are assumed to have already occurred. The actual ATO generation and routing of aircraft according to mission type is outside the scope of this thesis project.

STORM models time and space implicitly by describing time and space in terms of a discrete hierarchy. Air-to-air combat is broken down into engagements, and these engagements are broken down into phases. The phases are composed of a series of volleys so that "...weapons expenditure and attrition can be calculated with higher fidelity and air-to-air analysis can be more transparent [28:9]." Therefore, the goal of the

STORM methodology is to remain "campaign" in its scope while drawing on "engagement" level principles to improve fidelity.

The air motion and detection manager object triggers the engagement outside of the air-to-air adjudication manager object. The air-to-air algorithm calculates the weapon expenditure and attrition that result from the engagement. The air-to-air engagement process is shown graphically in Figure 3 and will be discussed in detail in the following sections.

Table 2. STORM's Air-to-Air mission capabilities as tied to Air Force Doctrine

| STORM Mission Description | Air Force Doctrinal Mapping | | |
|---|---|---|---|
| | Core Competency | Function | Element |
| Fighter Sweep | Air & Space Superiority | Counter Air | Offensive Counter Air |
| Ground Alert OCA | Air & Space Superiority | Counter Air | Offensive Counter Air |
| Fighter Escort | Air & Space Superiority | Counter Air | Offensive Counter Air |
| Offensive BARCAP | Air & Space Superiority | Counter Air | Offensive Counter Air |
| Defensive BARCAP | Air & Space Superiority | Counter Air | Defensive Counter Air |
| Ground Alert DCA | Air & Space Superiority | Counter Air | Defensive Counter Air |
| HVA protection | Air & Space Superiority | Counter Air | Defensive Counter Air |

### 3.3.1   Engagement Initialization

The engagement begins with the initial tactical maneuvering of two opposing flight groups. The flight's aircraft are broken down into elements, with a user-defined minimum number of aircraft per element. Weapons are allocated in a uniform fashion in cases where full loads do not exist. The engagement generates three possible outputs – weapon expenditure, attrition, or an escape. At the end of the engagement, the surviving aircraft and unexpended weapons are returned to the original flights where mission logic (outside of the prototype) determines the package's behavior [28:10].
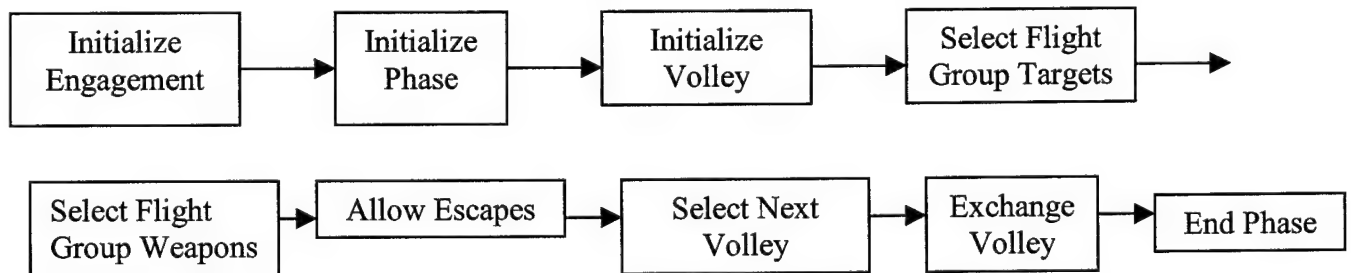


**Figure 3.   STORM Air-to-Air Methodology**

### 3.3.2 Phase Initialization

As mentioned previously, phases are used to capture time and space without explicitly modeling these concepts. These phases are controlled based on specific input. Other user-input data will be influenced by the definitions of these phases. Notice in Appendix B – D that the phases are used as the primary index for inputting data requirements. For example, when the probability of weapons effectiveness is needed for a particular weapon firing, the program determines the phase that is in progress, finds the appropriate phase under the probability of weapons effectiveness category (Appendix C), and locates the probability for that particular weapon type.

In the STORM air-to-air prototype, the designers have incorporated three phases – very long range (VLR), beyond visual range (BVR), and within visual range (WVR). These phases are sequential with a probability of escape, $P_e$, at each stage. Unlike BRAWLER, "looping back" into a previous stage is not allowed. A comparison of STORM's and BRAWLER's phases are depicted in Figure 4.



STORM: Sequential - Only path is from left to right

BRAWLER: Not Necessarily Sequential - Reentry into earlier phases
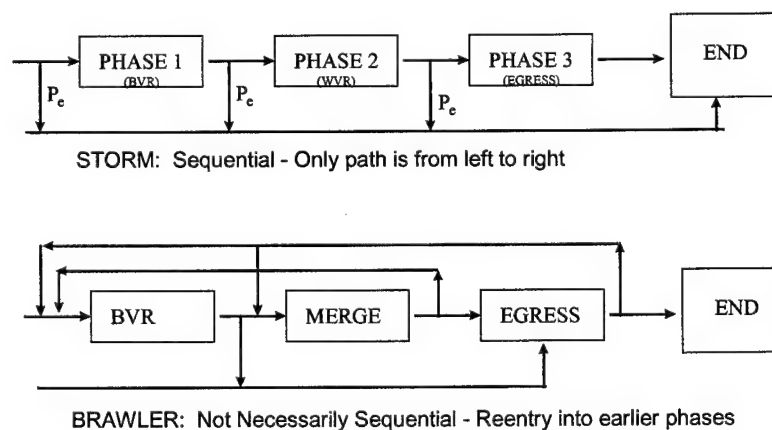
**Figure 4. STORM Versus BRAWLER Phase Paths** [24:15]

43

The phase concept is an innovative way of addressing the air-to-air combat environment for a campaign level model. Transparency is improved because tracking of combat events is improved. One word of caution though – because of eventual wide dissemination of the model, the definition of phases should be determined and agreed upon. Since the phases are the framework upon which the whole model is built, there should be some standardization of the distances that define a phase. One possible approach is to use BRAWLER to construct scatter plots of time and distance of firings. This reveals clusters of missile activity that could be used to define a phase [6]. These definitions should then be agreed upon by the user community.

During some of the calibration efforts, the developers have initially defined the phases in the following way. For the BVR phase, they assumed that all shots fired from one aircraft in fewer than 20 seconds were part of the same volley. In another phase, the time period was set to 10 seconds. The time distinction was made to account for the fact that at longer ranges, missile flight times are longer, and therefore so are periods between pilot assessments, and hence volleys [29:17].

There are issues concerning time and space that arise in a realistic air-to-air combat engagement that should also be taken into account, either explicitly or implicitly. When time and distance are modeled in this event hierarchy, limitations that arise from fuel limitations must be considered. Also, the position where the engagement occurs affects how the attackers and defenders respond to each other. Aircraft positions relative to the FLOT affect flight tactics and decisions. The final implementation of the algorithm into STORM should account for these issues.

44

### 3.3.3 Computation of Answered/Unanswered Volleys

STORM disaggregates the engagements into a series of volleys that make up a particular engagement. This more explicit modeling concept allows for a more accurate representation of munitions consumption and firing doctrine since each volley is separated by an assessment of the opponent's forces resulting from your attack.

Each of the three phases are subdivided into sets of discrete volleys. A volley is defined as an opportunity for aircraft to fire one or more salvos of one or more weapons against one or more targets.

There are two types of volleys, answered and unanswered. An answered volley is where weapons are exchanged and each side suffers attrition. An unanswered volley is where only one side fires and only the other side suffers attrition. The unanswered volley methodology is used to capture aspects of surprise of aircraft and range-advantages of certain weapons. This is a significant feature given the statistic that, historically, 80% of all aircraft shot in a real-life air-to-air engagement never detected the opponent that killed them [4:24].

Given that an opportunity for an unanswered volley exists, the algorithm first computes which side shoots the unanswered volley. This is determined by a ratio of user-defined probabilities that each side shoots the unanswered volley. That ratio is,

$$\frac{\text{Pr(side 1 shoots unanswered volley)}}{\text{Pr(side 1 shoots unanswered volley)} + \text{Pr(side 2 shoots unanswered volley)}} \qquad (22)$$

If this ratio is less than an pseudo-random generated number (uniformly distributed), then side 1 shoots the unanswered volley.

The probability of an unanswered volley is entered by the user in the A2A.DAT file shown in Appendix C. It is a function of phase, weapon, side's tactic (for instance - averse, medium, or tolerant), and opponent's weapon. For example, consider a fighter with a probability of 0.3 in the VLR phase with an AIM-54 with "tolerant" tactics versus the opponent's AA-9 munition. Further, suppose the opponent's probability of shooting his AA-9 in VLR stage with "averse" tactics versus the AIM-54 is 0.1. The calculation would result in a ratio of 0.75. Thus, side 1 would have a 75% chance of shooting an unanswered volley.

The probability of an unanswered volley has the versatility to be tied to a particular platform. This is fortunate because it should take into account the on-board systems when determining this probability. An AIM-120, for instance, should have a different probability firing from an F-15 than an F-16. The reader should begin to see the additional data burden that comes with the added versatility. These probabilities are necessary for every phase, tactic, and weapon combination. While this modeling approach provides a more realistic representation, it is not clear where an analyst can find all of these probabilities.

The maximum potential number of both answered and unanswered volleys is computed for all possible shooter–target pairs. Total volleys are the number of opportunities (taken or not) a given aircraft/weapon pair has to fire a volley against aircraft in an opposing flight. The maximum potential number of volleys is calculated for every weapon against every potential opposing flight. Only weapons that are employable in the specific phase are considered in the calculation. The maximum number of

unanswered volleys is drawn from a triangular distribution with the minimum, mode, and maximum input by the user. This data is designed to be "...derived directly from higher resolution models that represent the specific characteristics of and interactions between the aircraft and weapons involved in the engagement" [28:11]. The triangular distribution was chosen to make data development easier. This value is entered in the A2A.DAT shown in Appendix C file by phase, weapon, tactic, and target class. Target class is a particular category where an opponent is categorized, such as fighter, bomber, or other. Fractional draws from the triangular distribution are randomly rounded up or down to form an integer value.

The developers of STORM underwent an extensive calibration process in an attempt to adjust the input variables of the STORM adjudicator to that of BRAWLER. During this process, they discovered that a triangular distribution may not be appropriate because the necessary parameters of minimum, mode, and maximum are not readily collected from BRAWLER. The problem lay in the oversimplification forced by the triangular distribution and the fact that the computed mode was really the mean volleys taken in BRAWLER. The problem is illustrated by Figure 5 [29:18].
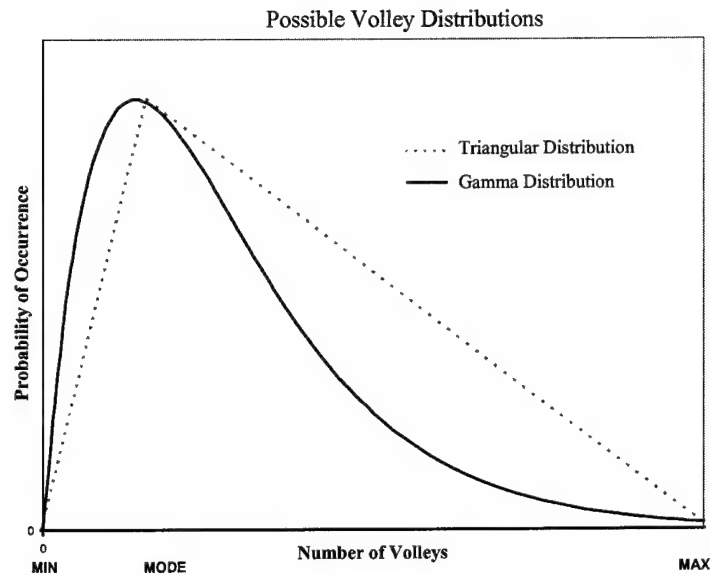
Figure 5.  Gamma and Triangular Distributions

Since the actual shot and volley distribution more closely represents a gamma

distribution like the one shown above rather than a triangular one, the average number of

shots produced was consistently too high.  The maximum, therefore, was tuned to give

the correct average.  This causes the prototype algorithm to lose some of its ability to

adequately represent the rarely occurring upper end of the volley spectrum.  The

developers have chosen to remedy the problem in the production version of STORM by

allowing the user to define the type of distribution used in determining volley

computation [29:17].

When a number is drawn from one of these continuous distributions, the

developers of STORM have chosen the following algorithm to randomly round all

decimal values higher or lower:

48

Let D = Random number drawn from appropriate         (23)
        distribution given parameters set by the user

Let I = Truncate (D)

Let D = D – I

If $R.N.[0,1] \leq D$:  Add 1 to I

Return I

The algorithm then computes the number of unanswered volleys that the particular side shoots. This is computed by a series of random sample draws from a binomial distribution. The probability of success is the same probability used above, *i.e.* the probability that the particular side shoots the unanswered volley. For the binomial draw, the number of trials from which the sample is taken is the "max unanswered volley" calculation described above.

### 3.3.4   Volley Adjudication

The volley is initialized by a computation of the force ratio of the opposing flight groups. Each flight group score is computed by summing the scores of the individual elements. The scores of the individual elements are found by adding together the user-input element configuration scores by type aircraft and munition. The force ratio is computed using the following equations:

$$BlueForceRatio = \frac{BlueConfigurationScore}{RedConfigurationScore} \qquad (24)$$

$$RedForceRatio = \frac{RedConfigurationScore}{BlueConfigurationScore}$$

The flight group command and control capability is also initialized at the beginning of the volley sequence. The user has the ability to enter a flight group command and control capability value, expressed as a percentage. This is to simulate the "...degree of inter-flight coordination reflecting the contribution of external systems (AWACS, GCI, *etc.*) as well as onboard aircraft systems (datalink, voice, *etc.*) and pilot training [28:10]." This parameter may be dynamically adjusted according to user-defined rules based on the availability and condition of relevant systems. Using this user-defined percentage, a random number draw determines if a flight group has command and control and signals a "flag" to the rest of the algorithm. If the random number is less than the command and control value, then the flight group does not have command and control, otherwise, it does.

The presence or absence of command and control affects the perceived number of enemy aircraft. If a flight group has command and control, the number of perceived enemy aircraft is equal to the actual number of aircraft. If the flight group does not have command and control, the perceived number of enemy aircraft is drawn from a normal distribution with the following parameters:

$$\mu = \textit{Actual Number of Enemy Aircraft} \tag{25}$$

$$\sigma = (1 - \textit{FGCC}) * \mu$$

where,

$\textit{FGCC}$ = The flight group command and control specified by the user.

50

As seen in Figure 6, as the number of aircraft increases and the *FGCC* decreases from perfect command and control (*FGCC* = 1) to no command and control (*FGCC* = 0), the standard deviation increases for each scenario. This is consistent with reality. As the number of red aircraft increases and the blue flight group command and control decreases, the blue aircraft are more likely to incorrectly guess the number of red aircraft.

The perceived number of aircraft is randomly rounded up or down to the nearest whole number using the same algorithm (23) that rounds the triangular distribution. The same concern applies that was discussed previously about using a uniform rounding rule to round the numbers up or down.

Also initialized, is the desire to escape of the individual flight groups. If the force
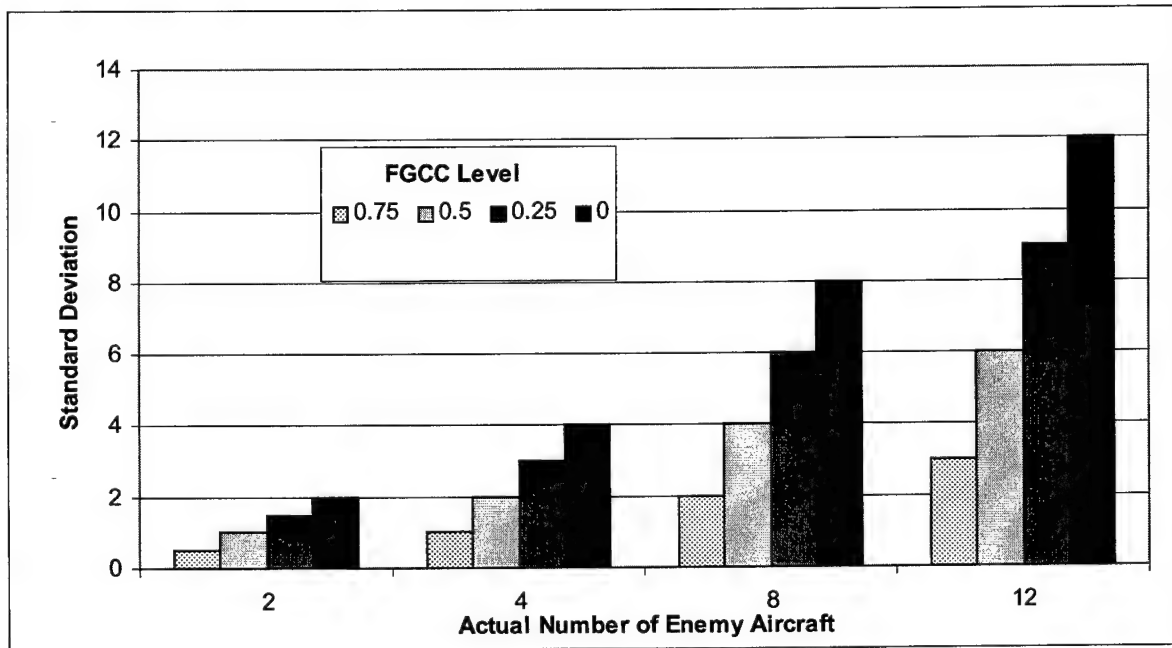


**Figure 6. Standard Deviation of Perceived Number of Aircraft**

ratio drops below the user-input force ratio threshold (example of ESCAPE.dat file shown in Appendix D), the individual element will desire to escape and will continue to desire to escape through the remaining phases. Also, an element's desire to escape is based on the number of weapons that the element has. If the total air-to-air configuration score for that element drops below a specified threshold, that element will desire to escape. The force ratio is computed using (24). Notice that it uses the actual score of the enemy aircraft and not the perceived score. This raises concerns that will be discussed in the next section.

Once all of the initialization processes are completed, the volley adjudication follows five main steps – targeting decisions, weapon selection and expenditure, escape decision and result, and attrition calculation.

### 3.3.4.1 Targeting Decision

The opponent "perceived score" is also initialized at this stage. The perceived score is computed as:

$$Perceived\ Score = Tot\ Number\ of\ Aircraft\ *\ \text{Max}(Configuration\ Score,\ Minimum\ Perceived\ Score) \tag{26}$$

The minimum perceived score is a user-specified input in A2A.dat (see Appendix C). As shown from (26), the maximum of either the configuration score or the minimum perceived score is used. Notice that the perceived score is based on the actual total number of aircraft. It seems that the perceived number of aircraft should be based on the *perceived* number of aircraft using a distribution draw discussed previously in (25) rather than the actual number of aircraft. This score is attempting to quantify one side's

52

perception of the opponent's capabilities. Therefore, this score should then be based on the number of aircraft that the side believes the opponent has.

During the targeting decision portion of the algorithm, each flight group's elements are grouped against flights of the opponent. The aircraft of a particular side are first sorted by the aircraft-munition configuration score from highest to lowest, and the opponent's side is sorted by perceived flight score. The force ratio computation determines the number of elements to target a particular flight and is given by:

$$BlueForceRatio = \frac{BlueConfigurationScore}{RedPerceivedScore} \qquad (27)$$

$$RedForceRatio = \frac{RedConfigurationScore}{BluePerceivedScore}$$

The perceived score is computed using (26). Blue elements are allocated to Red flights until this force ratio is greater than 1. This process allocates friendly elements to enemy flights and is performed by both sides. An element can be assigned to one and only one enemy flight within a single volley. Once the force ratio has been exceeded for all opposing flights, the remaining friendly flights do not target anyone. Over multiple volleys, a single element may engage multiple flights.

Notice that the force ratio used in computing the desired force ratio is based on the opponent's perceived platform configuration score. It seems that the equation for the ratio in (24) to compute the desire to escape should be computed in the very same way. It should also be based on the perceived score of the opponent. Notice that (27) contains the perceived score in the denominator while (24) contains the true configuration score.

The desire to escape should also be determined based on the number of aircraft the friendly side *perceives* the opponent has.

As the algorithm is designed currently, the enemy flights are sorted highest to lowest and the friendly elements are sorted highest to lowest. The greedy algorithm described above allocates the friendly elements to the flights with the highest perceived air-to-air configuration score until the desired force ratio is reached. This may work best for most situations, but it does not take into account the presence of high value assets (HVA). A possible HVA scenario may include a flight of MIG-29s engaging a flight of F-15s escorting B-1s in enemy airspace enroute to bombing a target. Depending on the existing force ratio, the MIG-29s in reality may place a high priority on targeting the B-1s, bypassing the F-15s. This is just one example in reality where a friendly element may chose to target a known HVA and try to circumvent the fighters that may have a high configuration score. This is currently not modeled in the algorithm. An HVA may have a low aircraft configuration score and would therefore be lower in priority to target by the opponent.

### 3.3.4.2 Weapon Selection and Expenditure

Weapon selection is also accomplished for every element against the opposing flights with munitions preferences specified by the user according to phase. The algorithm looks for the first item on the list in order of preference that does not have a probability of weapons effectiveness ($P_{we}$ – also a user-input value) equal to zero and more than zero volleys remaining.

The maximum number of weapons and targets is then computed as a function of user-input values. A salvo is a set number of weapons to fire at each aircraft. Each type of aircraft may have the ability to multi-target and the potential to fire salvos at up to that number of different enemy aircraft. The number of salvos is computed as follows:

$$Salvos = \frac{\min(NumberofAirMunitions, MaxTgts * MaxWeaponsPerTgtPerVolley)}{MaxWeaponsPerTgtPerVolley} \quad (28)$$

where,

$$MaxTgts = NumberInElement * MaxTgtsPerVolley$$

The total shots within a volley are limited by munition availability as well. Salvos are allocated to the enemy flights starting from the aircraft with the greatest air-to-air ability (determined from the aircraft-munition configuration score) [28:12].

The shots are then allocated individually to the target aircraft. At this point, the element command and control is significant. The allocation of shots can range from an optimal (*i.e.*, even) distribution to a random distribution of salvos to target aircraft depending upon the command and control of the elements involved. The allocation of random shots from a lack of command and control can result in some enemy aircraft being double targeted.

### 3.3.4.3  Escape Decision and Result

The desire to escape calculation is accomplished in the volley initialization process discussed previously. The actual ability for an element to escape comes before the volley exchange and is based on the current phase, disparity in force ratio, and the

types of opponents engaged. First, the probability of escape is calculated using user-input values.

$$\Pr(Escape) = \frac{1}{1 + \alpha \cdot \exp(-\beta \cdot ForceRatio)} \tag{29}$$

Where, (30)

$$\beta = \frac{(\log(\frac{1 - Y_1}{Y_1}) - \log(\frac{1 - Y_2}{Y_2}))}{X_2 - X_1} \tag{31}$$

$$\alpha = \exp(\beta \cdot X_1 + \log(\frac{1 - Y_1}{Y_1})) \tag{32}$$

*Force Ratio* (Flight Group 1) = (Flight Group 1 Score) / (Flight Group 2 Score)

or

*Force Ratio* (Flight Group 2) = (Flight Group 2 Score) / (Flight Group 1 Score)

and,

$X_1$ = Low Force Ratio

$Y_1$ = Low Probability of Escape

$X_2$ = High Force Ratio

$Y_2$ = High Probability of Escape

$X_1, Y_1, X_2, Y_2$ are input by the user according to phase and category of aircraft as shown in Attachment D. This distribution works well to accommodate a large variety of

situations that would develop. Figure 7 shows how the distribution changes as alpha is increased. Figure 8 shows the distribution changes as beta is increased.
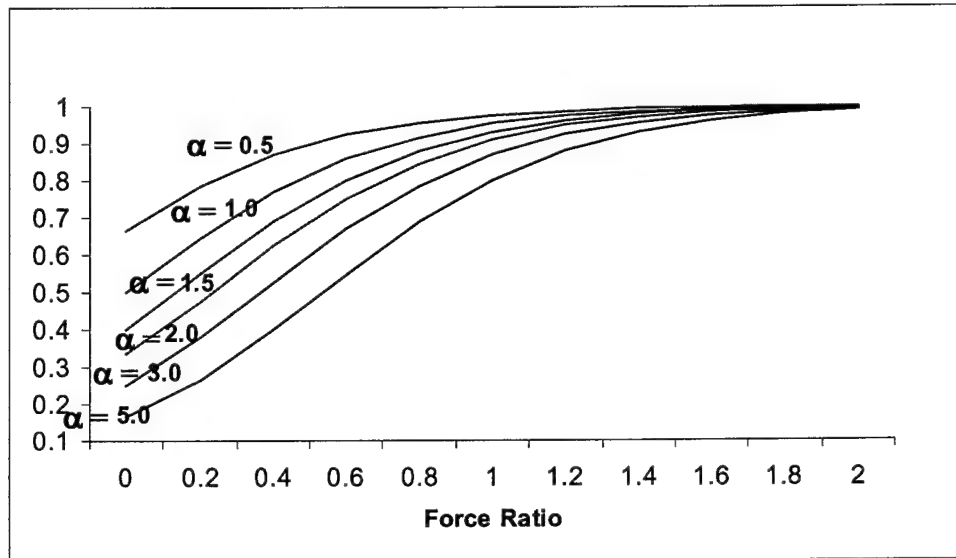


**Figure 7. Increasing Alpha in Escape Function**
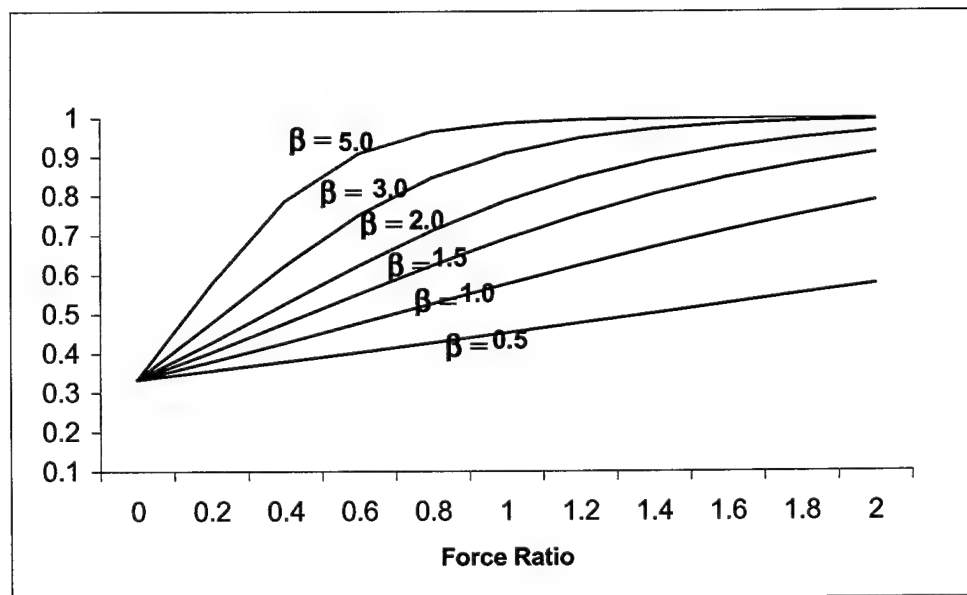


**Figure 8. Increasing Beta in Escape Function**

For example, consider the case of a bomber trying to escape from enemy fighters. Say that the user inputs the following combinations to describe a fighter against a bomber:

- For a low force ratio of 1 blue to 5 reds (0.2), there is the probability of escape of 0.20

- For a high force ratio of 5 blues to 1 red (5), there is a probability of escape of 0.50

After these values are input into (30) and (31), Figure 9 shows the resulting distribution for (29). If the actual force ratio turned out to be 5 blues to 1 red, the bomber would have around an 18% chance of escaping. This function can be tailored to meet the likelihood of an escape for any aircraft combination that participates in the engagement.
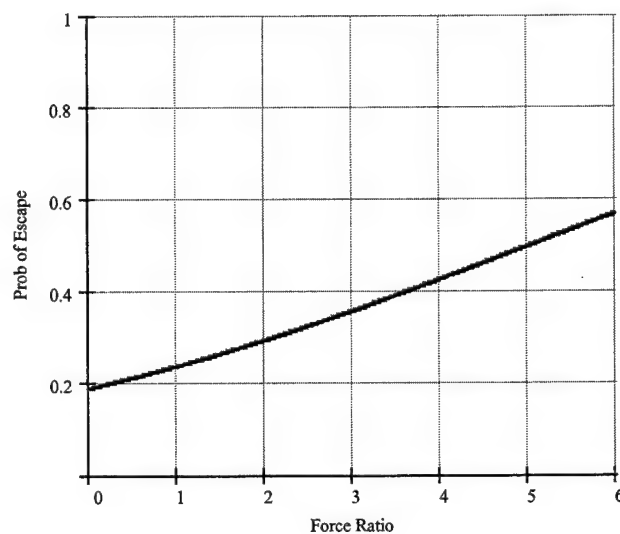


**Figure 9.  Example Case for Escape of Bomber vs Fighter**

For another example, consider a fighter escaping from a less capable fighter, such as a F-15A from a MIG-21. Say that the user inputs the following combinations to describe a fighter against another fighter:

- For a low force ratio of 1 blue to 5 reds (0.2), there is the probability of escape of 0.40

- For a high force ratio of 5 blues to 1 red (5), there is a probability of escape of 0.70

This would result in the function shown in Figure 10 describing the F-15A's ability to escape for a variety of force ratios. If the actual force ratio turned out to be 2 blues to 1 red, the F-15A has at least a 50% chance of escaping.
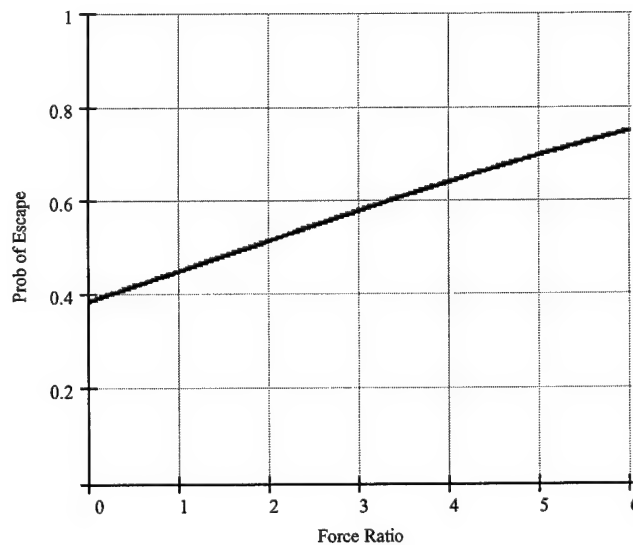


**Figure 10. Example Case for Escape Bomber vs Fighter**

Aircraft can be grouped according to their ability to escape. The probability of escape is scaled by the fraction of the phase that the element wanted to escape.

Also, a bias can be input by the user to account for the timing of the escape opportunities. For instance, all escape opportunities may occur before the first or last volley or may be equally distributed among all volleys. In highly advantageous force ratio conditions, even the slowest most vulnerable aircraft may be able to escape easily. Conversely, when heavily outnumbered by highly capable systems, even an advanced aircraft may have difficulty escaping in a WVR engagement. A probability of successfully egressing the engagement is selected based upon these factors [28:12].

### 3.3.4.4 Attrition Calculation

After shots have been allocated and munitions are consumed, attrition is calculated based upon the random draws against the user-input probability of weapon effectiveness ($P_{we}$). $P_{we}$ represents the probability of kill given a firing at an alert enemy target. The $P_{we}$ (shown in Appendix C) is a function of the shooter, weapon, shooter's tactics, target, and target's tactics involved. This data value requirement was designed to be gathered from higher-resolution models. An aircraft is killed if a random number from a $U(0,1) > (1 - P_{we})$.

Once that an aircraft is killed, STORM accurately accounts for the lost munitions associated with that killed aircraft. The algorithm specifically subtracts those munitions as lost in the engagement.

Possible problems may arise in possible "double dipping" between the $P_{we}$ and the probability of an unanswered volley. As the data definitions and values are determined, either by testing, SMEs, or calibration with lower models, the definitions and differences between these two data requirements should be understood by all parties involved. Otherwise, when determining the probability of an unanswered volley, there may be confusion regarding the probability that the weapon shoots down the target first.

During the developers calibration efforts, the $P_{we}$ was linked to the $P_{weaponeffect}$ from BRAWLER. These values were modified, however, based on the number of "Fuze on Dead Target" missiles. Dead Target Fuzings would most likely be caused by two separate aircraft shooting at the same target, which would be less likely given sufficient Command and Control. Since STORM models Command and Control separately, and Command and Control affects the number of targets seen and target apportionment, using a $P_{weaponeffect}$ which was already attenuated by "Fuze on Dead Targets" would double count this effect and result in a lower $P_{we}$ than originally intended. Therefore, the developers corrected this problem with this equation [29:16]:

$$\text{STORM } P_{we} = Kills/(Shots - Fuzes \ on \ Dead \ Targets) \tag{33}$$

An experiment was conducted to verify the reasonableness of the attrition for various engagement scenarios. A flight of F-15Cs with tolerant tactics engage MIG-29s also with tolerant tactics. The F-15Cs carried the AIM-120 and the AIM-9X. The MIG-29s carried AA-10 and AA-11 missiles. Average kills over 100 replications were measured for the following F-15C versus MIG-29 engagements: 12v12, 2v12, 2v4, 2v8, 4v4, and 8v8. Figure 11 shows the results from each of these engagements. The exchange ratio at
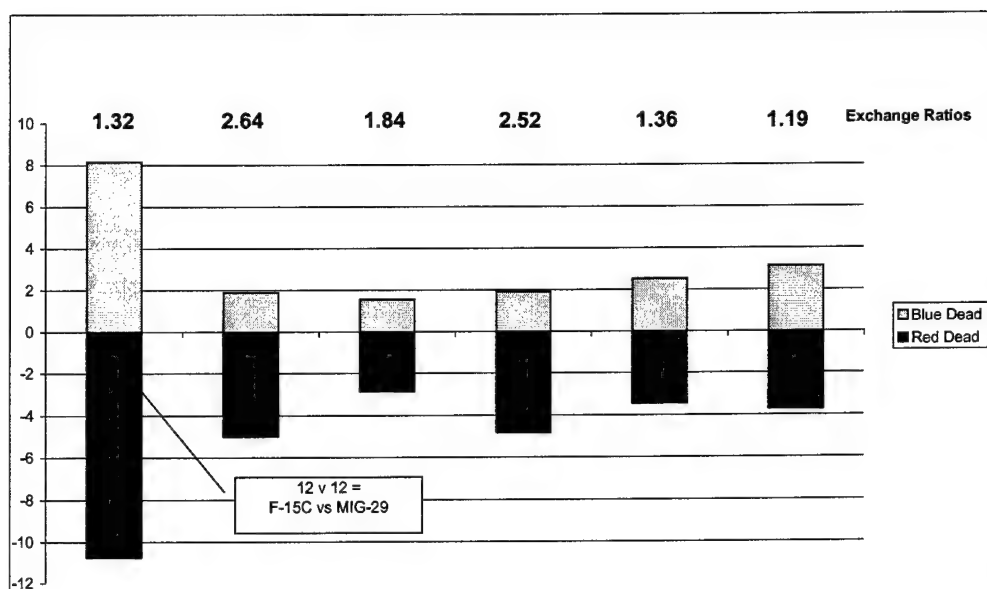
**Figure 11. Results of Various Force Ratio Engagements**

the top of the graph is an indicator to the relative performance of one side to the other.

The exchange ratio is equal to the number of blue kills (red dead) divided by the number

of red kills (blue dead). The model performed as expected given the input parameters fed

into it. Due to the better input parameters given to the F-15C, it outperforms the MIG-29.

Even in the 2v12 case, the F-15s kill 5 MIGs before the F-15s are actually destroyed

themselves. The closest matchup seems to be the 8v8 case where each side destroys

approximately 3 adversaries.

## 3.4   Summary

This chapter has presented an overview of the STORM air-to-air adjudicator

methodology. Overall, STORM has captured most of the critical elements of the air-to-

air engagement process. Table 3 shows how elements of the air-to-air combat

environment are modeled either explicitly or implicitly.

62

| | Modeled Explicitly | Modeled Implicitly |
|---|---|---|
| Missions | | |
| Aircraft & Org Representation | √ | |
| Command & Control | √ | |
| Spatial Layout | | √ |
| Environment | | |
| Munitions & Expenditures | √ | |
| Tactics & Maneuvering | √ | |
| Sensor Performance | | √ |
| Detection | √ | |
| Identification | | √ |
| Electronic Warfare | | |

**Table 3. Elements of Air-to-air Combat Modeled by the STORM Adjudicator**

There were significant methodology improvements that model attrition and munitions consumption with a higher degree of fidelity than THUNDER.

Some of the aspects of air-to-air combat STORM models particularly well are:

- The phase concept improves overall transparency and captures most of the issues in the air-to-air combat environment appropriate to a campaign level model.

- The volley concept accurately represents munitions consumption.

- The probability of an unanswered volley realistically accounts for range advantages and can be tied to aircraft platform.

- When a random number is drawn from a normal distribution to define the number of perceived aircraft, the parameters for the mean and standard deviation of the perceived number of aircraft is accurately computed.

- The ability to escape is based on an innovative function that can be shaped by the user-input values.

- $P_{we}$ can be tied to the shooting aircraft platform.

- The tracking of lost munitions of killed aircraft is accurately accounted for.

Some areas of improvement and concerns are:

- Definition of phases should be determined and agreed upon by the users of STORM.

- Certain issues of time and distance should be modeled either inside or outside the adjudicator (*e.g.* fuel constraints and position relative to the FLOT affect engagement strategies)

- The perceived score of an opponent is based on the actual total number of aircraft instead of the perceived number of aircraft. It should be based on what the friendly believes the opponent has.

- There is some concern that $P_{we}$ there would be "double dipping" with the probability of an unanswered volley unless the definitions are clearly understood by users.

- The targeting decision does not include circumstances involving HVAs. An HVA may have a low aircraft configuration score and would therefore be lower in priority to target by the opponent.

The methodology presented in this chapter assumed that the data was available for modeling. The issue of data source and availability will be addressed in the next chapter where the weaknesses of THUNDER and STORM will be compared.

## 4. Comparison of the THUNDER and STORM Models

### 4.1 Introduction

The limitations of THUNDER have circulated within the user community for many years. Many complaints have merit, but others can be traced to misunderstandings due to a lack of knowledge of either the assumptions of THUNDER itself or how it operates. The developers of STORM have documented a subset of the user concerns. Phase II of this report occurred in September, 1998 [27]. The following is a sample of some of the complaints of the air-to-air adjudicator:

- "...THUNDER automatically expends missiles when an engagement is initiated based on the user-defined number of launches per engagement. Some of these are not adjudicated...while others are wasted on 'many-on-few' engagements."

- "...Weapon expenditures, stealth detection, command and control are all subjective and subject obscure input data. However, when calibrated properly with a model like BRAWLER, the results could not be easily dismissed. Probably the weakest area was the determination of when and where an engagement occurs. Both CAP and INTERCEPT methodologies are very weak. Weapon expenditures are probably the next biggest problem."

- "...it is difficult to link back to engagement level models and has limited utility for munitions expenditure studies."

- "It seems to work, but is not very well understood and somewhat mystical. Data inputs of relative range advantage, friendly fighter lethality, value of friendly loss, *etc.* are more subjective than objective, and their effects on air combat outcomes are not very straight forward."

THUNDER and STORM differ in their modeling approaches. THUNDER is a time-stepped, probabilistic representation of interactions occurring in air-to-air combat. STORM is a heuristic, event-oriented approach to modeling air-to-air engagements. STORM's methodology was chosen to improve transparency to users and to increase the resolution of campaign level air-to-air combat beyond THUNDER. This will improve the accounting of attrition and munitions expenditures in the air-to-air combat environment. Due to these different modeling approaches, it makes it more challenging to compare/contrast specific modeling issues across both models. Also, as mentioned previously, Denhard has identified four stated criticisms of the THUNDER air-to-air submodel: 1) single shot probability of kill and range advantage issues, 2) the number of weapons fired per engagement by an aircraft is the same for all air-to-air engagements regardless of type of opponent aircraft faced, 3) a SHOOT-SHOOT firing doctrine instead of the more typical USAF SHOOT-LOOK-SHOOT firing doctrine, and 4) does not allow for aircraft to disengage before weapons release [8:79]. These concerns will be addressed in the following sections.

## 4.2 Probability of Kill Calculation

The single shot probability of kill employed by THUNDER considers only the firing platform/weapon combination versus opponent platform and not the opponent's

67

weapon. Consider the example of an F-15C armed with an AIM-120 as its primary weapon and the AIM-9 as the secondary weapon. It is engaged by a threat aircraft armed with a BVR missile that is less capable than the AIM-120 but has a greater range than the AIM-9. In real life, the AIM-120 is likely to dominate the majority of engagements. This ends up negating the enemy's range advantage over the AIM-9. However, if the F-15C expends all AIM-120s during previous engagements, the range advantage of the opponent's weapon over the AIM-9 is not reflected because the probability of kill does not take into account the opponent's weapon. In other words, you cannot show a realistic difference between using it as a secondary munition (after the AIM-120, where the opponent's weapon does not cause a problem) versus using it as a primary munition (where the opponent's weapon would cause problems).

STORM solves this problem with the concept of unanswered volleys. Recall that the possibility of an unanswered volley takes into account a relative range advantage. This probability of an unanswered volley is input by the user according to phase, friendly weapon, friendly tactics, and opponent weapon. Therefore, since the probability is based partly on the opponent's weapon type, this value would show the advantage of the opponent's weapon over, say, the AIM-9, given that the AIM-120 was already expended.

### 4.3  Munitions Consumption

THUNDER's air-to-air model has been useful but "...suffers from limiting assumptions that oversimplify the problem" [28:7]. THUNDER is good at representing attrition but lacks the ability to accurately represent munitions consumption. One limiting assumption is the requirement that the user input the number and type of

weapons fired for *any* engagement. The user inputs this value according to the configuration of the aircraft and its mission. This limiting assumption is particularly troublesome where there are disparate force numbers between friendly and opponent aircraft.

STORM overcomes this problem through the use of the volley concept. The user specifies the maximum number of weapons to fire per volley by aircraft and munition type. Notice that this is "per volley" and not "per engagement." This allows for the shots to be fired and an assessment to determine if the aircraft were destroyed. This prevents over-shooting of opponent aircraft and more accurately model munitions expenditures. If a flight group does not have accurate command and control, there may be over-shooting of opponent aircraft, but this is intentionally modeled to account for this possible real-world situation.

An experiment was conducted on the STORM air-to-air adjudicator to compute the number of munitions expended across a variety of force ratio scenarios. All scenarios involve F-15Cs versus MIG-29s, both fully loaded with "tolerant" tactics strategy. 100 replications were conducted for each scenario. Figure 12 displays the average number of weapons expended in STORM for each scenario by munition type. The figure also shows the number of weapons expended in THUNDER. The solid line shows the total number of munitions expended in THUNDER for the red forces (AA-10s and AA-11s), and the dotted line shows the total number of munitions expended in THUNDER for the blue forces (AIM-120s and AIM-9Xs). This assumes input into THUNDER of 2 shots per engagement.
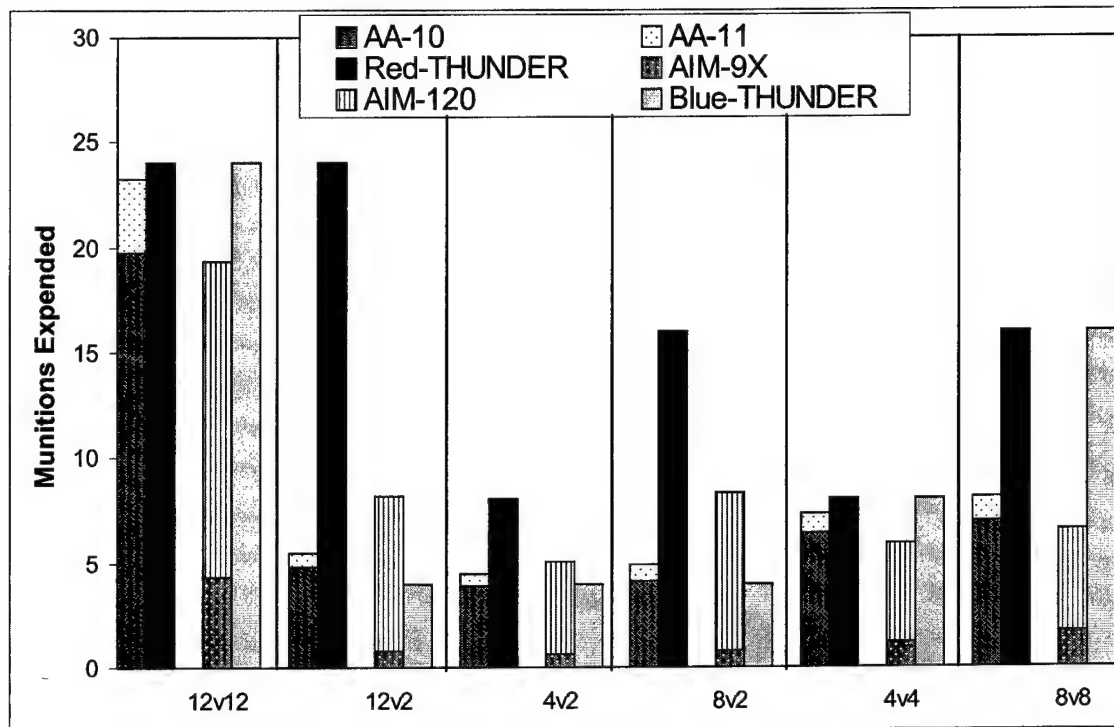
**Figure 12. STORM vs THUNDER Munition Expenditures**

Notice in the figure that in a scenario with disparate force ratios, such as 2v12 (2 F-15s versus 12 MIG-29s), that THUNDER calculates the blue side taking 4 shots and red side taking 24 shots. THUNDER has been criticized for not modeling munitions expenditures correctly in situations with a great disparity in force ratios – 24 red shots against only two blue aircraft is clearly overkill. In the STORM algorithm, the amount of munitions expended from the MIG-29s is more reasonable (Red: 5 AA-10s and 1 AA-11; Blue: 7 AIM-120s and 1 AIM-9X). In scenarios where the forces are smaller and more equally matched, such as a 4v4 case, the THUNDER modeling approach is acceptable. This experiment demonstrates that STORM corrects THUNDER's problem of inadequately modeling disparate force ratio scenarios.

## 4.4    Firing Doctrine

THUNDER treats a multiple missile salvo like a SHOOT-SHOOT firing strategy (which drives down the average single missile effectiveness) while BRAWLER treats a multiple missile salvo as SHOOT-LOOK-SHOOT firing tactic [8:79]. STORM disaggregates the engagements into a series of volleys that make up a particular engagement. This allows a more realistic representation of the Air Force doctrine of a SHOOT-LOOK-SHOOT firing strategy instead of a SHOOT-SHOOT strategy.

## 4.5    Escape Before Weapons Release

When an engagement occurs in THUNDER, weapons are always fired. The model does not allow for aircraft to disengage before weapons release. In the STORM adjudicator, this is corrected when the probability of escape calculation is performed. This calculation occurs *before* and after and in-between the unanswered and answered volley logic. This allows the aircraft to escape even before there is a single shot fired.

There are cases where one aircraft might fire its weapons, temporarily escape, re-engage, fire its weapons, temporarily escape, and continue this cycling strategy. Currently, the STORM adjudicator models this cycling strategy with the tactics concept, but this only occurs within the adjudicator itself. A situation where you have such a cycling strategy would be modeled with an averse tactic strategy. The result is that firing a missile at an averse aircraft would have a lower probability of success than a missile fired at a tolerant aircraft. Besides modeling with a tactics strategy, there are no other opportunities for modeling such a cycling strategy. When the algorithm is placed within STORM, the adjudicator should allow aircraft to escape completely, end the engagement,

71

and then re-engage to start a new engagement. In other words, the adjudicator could loop back to itself.

## 4.6 Data Requirements

The developers of STORM categorized some of the concerns about data requirements into several areas. First, there should be links to other models. Campaign models should be supported by data from engagement or mission level models. Automating these links and designing compatible assumptions in the campaign model methodology ensures an adequate data source. Many times this effort is complicated by the need for thousands of engagement model runs. Another goal is to provide for links to data repositories. Existing data repositories could be a source from which to gather input requirements. Many times this effort is complicated by the need for further "data massaging" in order to match the needed data requirement. Another goal is to provide for links to real world systems. Real world systems can be a source of timely data that may not have been considered a threat until a situation arises. The data requirements that are required for running STORM will be evaluated in light of these goals.

In association with ASC/ENMM, Table 4 (located at the end of this chapter) has been created to evaluate the various data requirements required in the STORM air-to-air algorithm. The categories of interest are the possible sources of locating such data, the possible security level, whether that data would be acquired from another model, and other comments or concerns. Most of the concerns listed in the comments heading have been addressed in the previous chapter.

Because the adjudicator is still in the prototype stage, some of the parameters are listed as *user* input but will be dynamic in nature when the actual model is implemented. Such things as ATOs, AEW coverage, and various mission types, done outside the adjudicator, will require that the input parameters be dynamic. Therefore, a caveat to this evaluation is that some of the data, such as command and control, will be affected by factors outside the adjudicator.

The overall evaluation of the data requirements reveals that many of the data requirements appear to be very subjective at this point. Much of the data will probably be gathered from consultations with a combination of SMEs and intelligence personnel. Some of the data will find its origin in such models as BRAWLER, but will require extensive "data massaging" to acquire correct results. It is highly recommended that a significant investment of time and resources be put into the development of such data. The adjudicator's ability to match reality will be determined by the data that is fed into the model. The next chapter will aid this process by determining the responsiveness of these data parameters and locating the most influential data parameters on the engagement outcome.

## 4.7 Summary

The STORM air-to-air adjudicator has improved upon the deficiencies of THUNDER. The particular areas of improvement are:

- The adjudicator's assessment of the volley logic overcomes THUNDER's problem of modeling munitions consumption in disparate force ratio scenarios.

- The concept of the unanswered volley takes into account the opponent's weapon type and improves THUNDER's probability of kill calculation.

- It allows for a more realistic representation of the Air Force doctrine of a SHOOT-LOOK-SHOOT firing strategy instead of a SHOOT-SHOOT strategy.

Some areas of possible improvement are:

- A goal of the adjudicator is to have data that is tied to data repositories and have links to real world systems. The source of many of these data requirements is questionable and seems subjective in nature. Combination of SME and calibration methods will be necessary to link to higher fidelity models such as BRAWLER. The data input to the STORM adjudicator is important because its ability to match reality will be determined by the data fed into the model.

Table 4. Comments on STORM Data Requirements    [13]

| | Data Source (SME, Intel, etc.) | Security Classification of Data Requirement | Data Input from Other Models? | Comments |
|---|---|---|---|---|
| **A.  File "Type"** | | | | |
| 1.  Specify Typical Element Size for Aircraft of Same Type | SME, Intel | Secret | Similar to BRAWLER min, max flight size | None |
| 2.  Number of each weapon the element will have | Threat AIRCRAFT- Intel US – Aircraft Tech Orders | Threat – Secret US – Unclass. | None | Depends on situation and what weapons are carried.  Could assume full load. |
| 3.  Percent Command & Control of Flight Element | SME | Unclass. | BRAWLER | Very Subjective.  Must account for radar reliability, Comm Equipment, etc. |
| 4.  Score Whereby Flight Element Desires to Escape | SME (Tactics Developers – e.g. Fight Weapons School) | Secret (Threat dependent) | None | THUNDER does not account for this.  Same as the direct input into BRAWLER. |
| **B.  File "A2A"** | | | | |
| 1.  Categorize weapon into Phase | Jane's – Based on general range data | Unclass. | None | Definitions of Phase MUST be agreed to by all parties involved.  Recommend standardization. |

75

| Item | Source | Classification | Model | Comments |
|---|---|---|---|---|
| 2. Max Number tgts /volley by aircraft by munition | SME Threat – Intel | Unclass. | None | In BRAWLER, dependent on fire control equipment and pilot skill level. Not modeled in THUNDER. |
| 3. Max Number wpns /tgt/volley by aircraft by munition | Threat – Intel US – Test data (fire control), SME | Secret | BRAWLER | None |
| 4. Air-to-air score for each type aircraft by munition | SME | Secret | Possible use of BRAWLER | Subjective unless use objective ranking system. The question can be asked, "How many reds make them equal to my 1 blue?" Need to account for radar effectiveness & missile performance. |
| 5. Minimum Perceived Score for each type aircraft | SME, Intel Possibly | Unclass. | None | None |
| 6. Probability of Weapons Effectiveness by phase by weapon by target by tactic | Test data calibrated with BRAWLER or Mission Level Model | Secret | BRAWLER or SUPPRESSOR or EADSIM | Same Input into BRAWLER (with modifications). The effectiveness of the weapon is affected by the type of aircraft shooting it. |
| 7. Max Number of Volleys by phase by munition versus by tactic vs. a particular type of aircraft | SME | Unclass. | None | More dynamic because affected by the mission type. |
| 8. Probability of an Unanswered Volley by phase by munition by tactic vs. particular weapon | SME, Intel | Secret | Possible use of BRAWLER | This data requirement is platform specific due to the dependence on radar performance. |

| | | | | |
|---|---|---|---|---|
| **C. File "Escape"** | | | | |
| 1. Set aircraft into desire-to-escape "classes" | Threat – Intel US – SME | Secret (Possibly Secret) | None | Would probably assume they have their best. |
| 2. Probability of Escape by phase by escape class by opponent's escape class | SME | Unclass. | None | Subjective |
| 3. Timing of Escape Opportunity (before first volley, equally distributed across all volleys, or after last volley) | SME | Unclass. | None | Subjective |
| 4. Force Ratio whereby opposing forces would desire to escape | Threat – Intel SME | Unclass. | None | Subjective |
| **D. File "Engage"** | | | | |
| 1. Specify a tactic for aircraft in a flight group | SME – *e.g.* Fighter Weapons School | Secret | None | Very dependent on mission type. |
| 2. Percent Command & Control for a Flight Group | SME | Unclass. | None | Subjective. Mission Specific (AWACS, GCI coverage?). |
| 3. Number of aircraft in Flight Group | Campaign Air Tasking Order | Secret | None | Very dependent on mission type. Can use mission model to generate packages. Use engagement level model to observe results of combinations. Then calibrate. |

# 5. Sensitivity Analysis

## 5.1 Introduction

In order to evaluate the effectiveness of the implementation of STORM's air-to-air adjudicator, an experiment was conducted examining the sensitivity of various user input data. The purpose of the experiment is twofold. First, determine if the algorithm is sensitive to air platform changes so that it can be validly used for comparing competing systems and strategies. Second, identify the most influential factors. Due to the synergistic effect of the varying input values, it is difficult to say without experimentation which ones are most influential. Once the most influential factors are identified, the developers and the users in the field will know which "control knobs" are most important in determining the outcome of the engagement(s).

## 5.2 Scenarios

Two phases, BVR and WVR, and two tactic types, AVERSE and TOLERANT were used for this experiment. In order to evaluate various control settings, a standard engagement was used composed of 8 F-15C's versus 8 MIG-29's, with the MIG-29 having tolerant tactics. The number of aircraft was chosen so that the engagement kills on either side would not plateau at zero. The MIG-29's armament is composed of 4 AA-10s, 4 AA-11s, and 5 gun salvos. Each F-15 is carrying 4 AIM-120 AMRAAM long-range missiles, 4 AIM-9X missiles, and 5 gun salvos. The MIG-29's control settings were left at reasonable settings and were not changed throughout the experiment. It was decided to change the input settings for only the AIM-120 AMRAAM due to the combinatorial nature of the problem.

## 5.3    Design of Experiment

The design of the experiment was a 2-level half fraction design with seven factors – maximum targets per volley (Mtgts), maximum weapons per target per volley (Mwpns), air-to-air configuration score (Score), probability of weapon effectiveness (Pwe), maximum volleys(MaxVol), probability of an unanswered volley (Puv), and tactic.

When one can assume that certain high-order interactions are negligible, then information on the main effects and low-order interactions may be obtained by running a fraction of the complete factorial. The one-half fraction of the $2^7$ design was chosen and results in a resolution VII experiment. This resolution number indicates that main effects are aliased with six factor interactions and higher. Two factor interactions are aliased with four factor interactions and higher. Three factor interactions are aliased with other three factor interactions and higher. Therefore, a resolution VII is sufficient to determine the main effects and any low order interactions. A $2^{7-1}$ experiment results in 64 total runs [21:134,158].

The design matrix is shown in Table 5. Minus values signify low settings and positive values signify high settings. Column G, tactic, is defined by the relation, G = ±ABCDEF.

## Table 5. Design Matrix

|   | A<br>Mtgt | B<br>Mwpn | C<br>Score | D<br>Pwe | E<br>MaxVol | F<br>Puv | G<br>Tactic |
|---|---|---|---|---|---|---|---|
| 1 | -1 | -1 | -1 | -1 | -1 | -1 | 1 |
| 2 | 1 | -1 | -1 | -1 | -1 | -1 | -1 |
| 3 | -1 | 1 | -1 | -1 | -1 | -1 | -1 |
| 4 | 1 | 1 | -1 | -1 | -1 | -1 | 1 |
| 5 | -1 | -1 | 1 | -1 | -1 | -1 | -1 |
| 6 | 1 | -1 | 1 | -1 | -1 | -1 | 1 |
| .... | .... | .... | .... | .... | .... | .... | .... |
| 62 | 1 | -1 | 1 | 1 | 1 | 1 | -1 |
| 63 | -1 | 1 | 1 | 1 | 1 | 1 | -1 |
| 64 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Mtgt = Max number of targets per volley | | | Pwe = Probability of weapons effectiveness | | | | |
| Mwpn = Max number of weapons per target | | | MaxVol = Maximum number of volleys | | | | |
| Score = Air-to-air configuration score | | | Puv = Probability of an unanswered volley | | | | |

Because the variability of the sample runs was unknown, approximately 30 replications were done for each of the 64 runs.

## 5.4    Parameters

Table 6 summarizes the factor settings used corresponding to the matrix of Table 5.

## Table 6.  Factor Settings

|   | Factors | | | | | | |
|---|---|---|---|---|---|---|---|
|   | Mtgt | Mwpn | Score | Pwe | MaxVol | Puv | Tactic |
| **High** | 4 | 2 | 75 | 0.75 | 2.5 | 0.7 | Tolerant |
| **Low** | 3 | 1 | 55 | 0.3 | 1 | 0.3 | Averse |

80

The "low" setting represents this study's worst airframe/armament capability, with "high" being the best. The settings were chosen based on a data file delivered with the adjudicator prototype.

## 5.5  Measure of Effectiveness

One measure of effectiveness was chosen to best demonstrate sensitivity to various input changes. The outcome that is of most interest to a user of this algorithm is the number of kills on each side. Although blue and red kills are of interest by themselves, the exchange ratio takes both of them into account. The formula for the exchange ratio is:

$$\textit{Exchange Ratio} = \textit{Blue Kills / Red Kills} \tag{34}$$

## 5.6  Least Squares Linear Regression

Linear regression involves using independent predictor variables to estimate a model in order to predict a response. A first-order model is represented by the following equation:

$$Y = \beta_o + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_k x_k + \varepsilon \tag{35}$$

where Y is the response variable, $x_i$'s are the independent variables, and $\beta_i$'s are the regression coefficients which represent the expected change in response Y per unit change in $x_i$ when all remaining independent variables $x_j$ ($i \neq j$) are held constant. $\varepsilon$ is the error term which is assumed to be independent and identically normally distributed with a mean of zero and constant variance [19:110].

### 5.6.1 Testing for Significance of Individual Regression Coefficients

A t-test was used to ensure that only significant variables are included in the model. The null hypothesis is $H_o$: $\beta_j = 0$, and the alternative hypothesis is $H_A$: $\beta_j \neq 0$. If the null hypothesis is not rejected, the coefficient, $\beta_j$, for the $x_j$ variable is not significant, and $x_j$ is removed from the model. The test statistic is given by:

$$t_0 = \frac{b_j}{\sqrt{\hat{\sigma}^2 C_{jj}}} \tag{36}$$

where $b_j$ is the estimate of $\beta_j$, and $C_{jj}$ is the diagonal element of $(\mathbf{X'X})^{-1}$ corresponding to $b_j$, where $\mathbf{X}$ represents the matrix of independent x variables. The null hypothesis is rejected if $|t_0| > t_{\alpha/2, n-k-1}$, where n is sample size and k is the number of independent variables. A p-value was used to determine whether or not to include a variable in the model. A p-value is the smallest value of $\alpha$ for which the null hypothesis can be rejected [19:111]. For this study, a variable with a p-value of greater than 0.10 was considered insignificant.

### 5.6.2 Testing for Significance of Regression

It is also necessary to test whether the $\beta_j$ coefficients are significant. The null hypothesis is $H_o$: $\beta_1 = \beta_2 = \ldots = \beta_k = 0$, with an alternative of $H_a$: Not all $\beta_i$ equal zero. Rejecting the null hypothesis implies that at least one of the independent variables is significant to the model. The test statistic is:

$$F_o = \frac{SS_R / k}{SS_E / (n - k - 1)} = \frac{MS_R}{MS_E} \qquad (37)$$

where $SS_R$ is the sum of squares due to the model (or regression) and $SS_E$ is the sum of squares due to the residual (or error). The formulas for these estimates are:

$$SS_R = b'X'y - \frac{\left(\sum_{i=1}^{n} y_i\right)^2}{n} \qquad (38)$$

$$SS_E = y'y - b'X'y \qquad (39)$$

$H_o$ is rejected if $F_o > F_{\alpha, k, n-k-1}$. A p-value is computed for this test statistic to determine whether or not the model is significant. In this study, the model was considered significant if the p-value is less than 0.05.

The coefficient of multiple determination, $R^2$, is another estimate that implies the appropriateness of the model. $R^2$ is the measure of the amount of reduction in the variability of the response obtained from the independent variables used. The formula for $R^2$ is:

$$R^2 = \frac{SS_R}{SS_R + SS_E} \qquad (40)$$

However, adding an independent variable will always increase $R^2$, so a better measure is given by an adjusted $R^2$, which does not always increase with the addition of a variable. The formula for $R^2_{adj}$ is:

82

$$R^2_{adj} = 1 - \frac{SS_E/(n-p)}{(SS_R + SS_E)/(n-1)}$$ (41)

where $p$ is the number of $\beta_i$'s. Higher $R^2_{adj}$ values indicate a better fit to the data.

To verify that model assumptions are not violated, residual analysis was performed. This involves verifying that the error terms, $\varepsilon_i$'s, are independent and identically normally distributed with mean zero and constant variance. For this study, a scatter plot of the residuals against the predicted values was used to visually verify independence and constant variance. The Shapiro-Wilk test was used to verify normality. The null hypothesis of the test is that the distribution is normal. For this study, residuals with a p-value of less than 0.05 were considered non-normal [19:112].

## 5.7 Results

There was some question as whether to measure the number of kills on each side for just the phase that was being altered or whether to measure the number of kills across all phases. In order to capture the effects of one phase's outcome influencing the next, the number of kills and hence the exchange ratio was measured across all phases.

Based on several trial runs, it was determined that the overall experiment should be split into three separate experiments. One experiment would measure the exchange ratio while changing the input parameter to the AMRAAM in the BVR phase. Since there are no other missiles fired by the F-15 in the BVR phase, this would be adequate. Another experiment would measure the exchange ratio as the input parameters are changed on the AMRAAM fired in the WVR phase *first* on the priority list. Another experiment would measure the effects of the AMRAAM *second* on the priority list and

83

the AIM-9X being first in the WVR phase. An example of this priority list is shown in Attachment C. As discussed previously, the munition types that are able to be fired from the particular platform are chosen from this priority list until that particular munition type runs out. Then, the next munition type is chosen.

### 5.7.1  Response with Changes in the BVR Phase

A transformation of the responses was performed to obtain a predictive model. Transformations are often necessary to deal with problems of non-normality of residuals [22:296]. The transformation used was the inverse transformation of the responses. Table 7 summarizes the significant factors in terms of the coded factors.

In terms of actual factors, two equations are necessary because tactic is a significant qualitative variable instead of a quantitative variable. The response models are as follows.

When tactics are set low (averse), the equation is:

$$\frac{1}{Y} = 0.58 - 0.034 \cdot Mtgt - 0.068 \cdot Mwpn - 0.17 \cdot Pwe - 0.13 \cdot MaxVol - 0.084 \cdot Puv \qquad (42)$$

**Table 7. Significant Factors (BVR)**

| Factor | Coefficient Estimate | DF | Standard Error | t for H0 Coeff=0 | Prob > \|t\| |
|---|---|---|---|---|---|
| Intercept | 0.640336 | 1 | 0.012468 | | |
| Mtgt | -0.03442 | 1 | 0.012468 | -2.76108 | 0.0077 |
| Mwpn | -0.06845 | 1 | 0.012468 | -5.49012 | < 0.0001 |
| Pwe | -0.16971 | 1 | 0.012468 | -13.6118 | < 0.0001 |
| MaxVol | -0.13347 | 1 | 0.012468 | -10.7052 | < 0.0001 |
| Puv | -0.08397 | 1 | 0.012468 | -6.73495 | < 0.0001 |
| Tactic | 0.056103 | 1 | 0.012468 | 4.4999 | < 0.0001 |

When tactics are high (tolerant), the equation is:

$$\frac{1}{Y} = 0.70 - 0.034 \cdot Mtgt - 0.068 \cdot Mwpn - 0.17 \cdot Pwe - 0.13 \cdot MaxVol - 0.084 \cdot Puv \qquad (43)$$

The $R^2_{adj}$ (Table 8) is relatively high, and the model is significant as seen in Table 9.

The most influential factors, when the AIM-120 is varied using the high and low

settings, are (in order of influence):

1. Probability of weapons effectiveness

2. Maximum volleys

3. Probability of an unanswered volley

4. Maximum weapons per target per volley

5. Maximum targets per volley

**Table 8. BVR Summary of Fit**

| | |
|---|---|
| R-Squared | 0.876156 |
| Adj R-Squared | 0.86312 |
| Root MSE | 0.099741 |

**Table 9. BVR Analysis of Variance**

| Source | Sum of Squares | DF | Mean Square | F Value | Prob > F |
|---|---|---|---|---|---|
| Model | 4.01172 | 6 | 0.668619 | 67.2096 | **< 0.0001** |
| Residual | 0.567052 | 57 | 0.009948 | | |
| Cor Total | 4.57877 | 63 | | | |

85

### 5.7.2 Response with Changes in the WVR Phase, First on Priority List

The experiment was run inside the WVR phase while changing the AMRAAM first on the priority list. This priority list is shown in Attachment C. Once it was determined from the model above that two factor interactions were not significant, the experiment was changed to a $2^{7-3}$ resulting in a resolution IV experiment, making data gathering easier. This resulted in the design matrix in Table 10.

**Table 10. Amended Design Matrix**

|    | A<br>Mtgt | B<br>Mwpn | C<br>Score | D<br>Pwe | E<br>MaxVol | F<br>Puv | G<br>Tactic |
|----|-----------|-----------|------------|----------|-------------|----------|-------------|
| 1  | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| 2  | 1  | -1 | -1 | -1 | 1  | -1 | 1  |
| 3  | -1 | 1  | -1 | -1 | 1  | 1  | -1 |
| 4  | 1  | 1  | -1 | -1 | -1 | 1  | 1  |
| 5  | -1 | -1 | 1  | -1 | 1  | 1  | 1  |
| 6  | 1  | -1 | 1  | -1 | -1 | 1  | -1 |
| 7  | -1 | 1  | 1  | -1 | -1 | -1 | 1  |
| 8  | 1  | 1  | 1  | -1 | 1  | -1 | -1 |
| 9  | -1 | -1 | -1 | 1  | -1 | 1  | 1  |
| 10 | 1  | -1 | -1 | 1  | 1  | 1  | -1 |
| 11 | -1 | 1  | -1 | 1  | 1  | -1 | 1  |
| 12 | 1  | 1  | -1 | 1  | -1 | -1 | -1 |
| 13 | -1 | -1 | 1  | 1  | 1  | -1 | -1 |
| 14 | 1  | -1 | 1  | 1  | -1 | -1 | 1  |
| 15 | -1 | 1  | 1  | 1  | -1 | 1  | -1 |
| 16 | 1  | 1  | 1  | 1  | 1  | 1  | 1  |

An inverse transformation was also used for this portion of the experiment. Based on this transformation, Table 11 shows the significant factors.

The response models in terms of actual factors are as follows:

When tactics are set low (averse), the equation is:

$$\frac{1}{Y} = 0.70 - 0.66 \cdot MaxWpn \tag{44}$$

When tactics are high (tolerant), the equation is:

$$\frac{1}{Y} = 0.40 - 0.66 \cdot MaxWpn \tag{45}$$

The $R^2_{adj}$ (Table 12) is high, and the model is significant as seen in Table 13.

**Table 11. Significant Factors (WVR – First on Priority List)**

| Factor | Coefficient Estimate | DF | Standard Error | t for H0 Coeff=0 | Prob > \|t\| |
|--------|---------|----|----|----|----|
| Intercept | 0.552916 | 1 | 0.013983 | | |
| Mwpn | -0.06583 | 1 | 0.013983 | -4.70765 | 0.0004 |
| Tactic | -0.1518 | 1 | 0.013983 | -10.8561 | < 0.0001 |

**Table 12. WVR (First on Priority List) Summary of Fit**

| | |
|---|---|
| R-Squared | 0.915042 |
| Adj R-Squared | 0.901972 |
| Root MSE | 0.055932 |

**Table 13. WVR (First on Priority List) Analysis of Variance**

| Source | Sum of Squares | DF | Mean Square | F Value | Prob > F |
|---|---|---|---|---|---|
| Model | 0.438026 | 2 | 0.219013 | 70.0088 | < 0.0001 |
| Residual | 0.040669 | 13 | 0.003128 | | |
| Cor Total | 0.478695 | 15 | | | |

When the AIM-120's settings are varied in the WVR and it is first on the priority list, maximum weapons per target per volley and tactic are the most influential. Since a majority of the AIM-120s are shot in the BVR stage, it makes sense that a majority of the influential factors in the BVR experiment will drop out. Also, since changing the tactic in the WVR phase means changing the tactic in all phases (a plane has the same tactic for all phases), tactic should be a significant factor no matter what.

### 5.7.3 Response with Changes in the WVR Phase, Second on Priority List

Again, an inverse transformation was used for this portion of the experiment. Table 14 shows the significant factor based on this transformation:

**Table 14. Significant Factors (WVR – Second on Priority List)**

| Factor | Coefficient Estimate | DF | Standard Error | t for H0 Coeff=0 | Prob > |t| |
|---|---|---|---|---|---|
| Intercept | 0.5711 | 1 | 0.014419 | | |
| G-Tactic | -0.15854 | 1 | 0.014419 | -10.9959 | < 0.0001 |

The response models in terms of actual factors are as follows.

When tactics are set low (averse), the equation is:

$$\frac{1}{Y} = 0.70 \tag{46}$$

When tactics are high (tolerant), the equation is:

$$\frac{1}{Y} = 0.40 \tag{47}$$

The $R^2_{adj}$ (Table 15) is relatively high, and the model is significant as seen in Table 16.

As hypothesized in the previous experiment, when the AIM-120's settings are varied in the WVR and it is *second* on the priority list, tactic is now the most influential. By the time that platform gets to shooting the AIM-120, it has shot most of the other

**Table 15.  WVR (Second on Priority List) Summary of Fit**

| | |
|---|---|
| R-Squared | 0.896227 |
| Adj R-Squared | 0.888815 |
| Root MSE | 0.057674 |

**Table 16.  WVR (Second on Priority List) Analysis of Variance**

| Source | Sum of Squares | DF | Mean Square | F Value | Prob > F |
|---|---|---|---|---|---|
| Model | 0.402181 | 1 | 0.402181 | 120.91 | < 0.0001 |
| Residual | 0.046568 | 14 | 0.003326 | | |
| Cor Total | 0.448749 | 15 | | | |

missiles and achieved most of the kills. As stated previously, it makes sense that tactic is most important because an aircraft's tactic affects all of the phase outcomes.

## 5.8    Summary

Based on the results shown in this chapter, the battle outcomes are responsive to changes in the air-to-air parameters. The probability of weapons effectiveness, maximum volleys, and probability of an unanswered volley are the top three most influential on the outcome. This demonstrates the algorithm's ability to be used for comparisons and suggests which "control knobs" are most influential for the user.

# 6. Conclusions and Recommendations

## 6.1 Validation Assessment of the STORM Air-to-Air Adjudicator

This thesis effort has approached evaluation of this model from two angles. First, the algorithm itself underwent structural validation to identify any limitations and restrictive assumptions. It was compared to the real world keeping in mind the intended use of the model for campaign level analysis only. It was also compared to its predecessor, THUNDER, to ensure that it improved upon its weaknesses. Second, the result validation effort culminated in a design of experiment to evaluate the responsiveness of the model.

Data validation was accomplished to see if the data was available and appropriate. It was discovered that the adjudicator is largely data driven, and particular care should be taken to ensure that the data is accurate. It seems much of the data required will be available from higher fidelity models while other data requirements seem very subjective in nature.

Sensitivity analysis was used to determine the most influential input variables on the outcome of the engagement. It was determined that the probability of weapons effectiveness, maximum volleys, and probability of an unanswered volley are the top three most influential on the outcome. This demonstrates the algorithm's ability to be used for comparisons and suggests which "control knobs" are most influential for the user.

The bottom line is that STORM air-to-air adjudicator will prove to be a useful tool for campaign analysis in the new century. The review of the components of the

algorithm indicates that it has implemented the air-to-air combat process with a considerable degree of fidelity, although improvements can still be made. Although there are assumptions related to aggregation, it still reasonably represents the elements of the air-to-air combat environment. Some of the aspects of air-to-air combat STORM models particularly well are:

- The phase concept improves overall transparency and captures most of the issues in the air-to-air combat environment appropriate to a campaign level model.

- The volley concept accurately represents munitions consumption.

- The probability of an unanswered volley realistically accounts for range advantages and can be tied to aircraft platform.

- The parameters for the mean and standard deviation of the perceived number of aircraft is accurately computed.

- The ability to escape is based on an innovative function that can be shaped by the user-input values.

- $P_{we}$ can be tied to the shooting aircraft platform.

- The tracking of lost munitions of killed aircraft is accurately accounted for.

- The adjudicator's assessment of the volley logic overcomes THUNDER's problem of modeling munitions consumption in disparate force ratio scenarios.

- The concept of the unanswered volley takes into account the opponent's weapon type and improves THUNDER's probability of kill calculation.

- STORM allows for a more realistic representation of the Air Force doctrine of a SHOOT-LOOK-SHOOT firing strategy instead of a SHOOT-SHOOT strategy.

## 6.2 Recommendations

It cannot be over emphasized that the most important recommendation for improvement of the STORM air-to-air adjudicator is to place particular emphasis on the development of the data input. The acceptability of the output of engagements is dependent on the accuracy of the input data.

Other particular areas of improvement are:

- Definition of phases should be determined and agreed upon by the users of STORM.

- Certain issues of time and distance should be modeled either inside or outside the adjudicator (*e.g.* fuel constraints and position relative to the FLOT affect engagement strategies)

- The perceived score of an opponent is based on the actual total number of aircraft instead of the perceived number of aircraft. Should be based on what the friendly believes the opponent has.

- There is some concern that $P_{we}$ would promote "double dipping" with the probability of an unanswered volley unless the definitions are clearly understood by users of the adjudicator.

- The targeting decision does not include circumstances involving HVAs. An HVA may have a low aircraft configuration score and would therefore be lower in priority to target by the opponent.

- A goal of the adjudicator was have data tied to data repositories with links to real world systems. The source of many of these data requirements is questionable and seems subjective in nature. Combination of SME and calibration methods are necessary to link to higher fidelity models such as BRAWLER. The data input to the STORM adjudicator is important because its ability to match reality will be determined by the data fed into the model.

## 6.3    Final Thought

The STORM air-to-air adjudicator is an innovative model to meet the needs of campaign level air-to-air analysis. Any deficiencies listed in this thesis are opportunities for improvement when the first version of STORM is released.

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## Appendix A:  THUNDER Air-to-Air Missions

In accordance with USAF doctrine, THUNDER missions are defined by their objectives rather than the type of aircraft accomplishing the mission.  THUNDER defines 27 missions, grouped as air-to-ground missions, air-to-air missions, suppression of enemy air defense (SEAD) missions, and High Value Asset (HVA) missions.  The air-to-air missions defined in THUNDER are described in the following sections.

### A.1 Barrier Combat Air Patrol (BARCAP)

A BARCAP aircraft, while on-station, patrols a designated area on its own side of the forward line of troops (FLOT) in order to intercept any enemy aircraft that attempt to pass through the area.  It does not try to intercept specific threats but, instead, patrols a rectangular area, called the Combat Area Patrol (CAP), on its own side of the FLOT.  Upon passing the BARCAP area, a threat is subject to detection by the BARCAP aircraft.  If the threat is detected, an engagement will occur.  Multiple enemy flight groups in the BARCAP area at the same time are treated independently.  No saturation effect is considered.  After the engagement, surviving aircraft with air-to-air munitions remaining, continue to form a CAP.  When it can no long be maintained due to lack of fuel/weapons, the aircraft return to base [26:25, 35-37].

### A.2 Defensive Counter-Air (DCA)

A DCA aircraft sits on strip alert and flies in response to the enemy's penetrating attack.  The DCA is triggered by detection of the ingressing enemy flight group.  If the aircraft type's probability of enemy interceptor launch of the primary flight is less than one, a random draw is made to determine if the ingressing flight group will even be

considered for DCA. If selected, a search is made of all possible interceptors for the earliest possible intercept. If the side intercept ratio is not satisfied, more aircraft are sent, from possibly different bases. The DCA group will then fly to the predicted intercept point. It then checks to see if the enemy flight group is within radar detection. If detected, THUNDER decides if engagement occurs using the air-to-air engagement probability. If it takes off and fails to intercept the enemy, it acts exactly like a BARCAP aircraft, using its intercept point as the center of an orbit and circling on-station, waiting for threats, as long as fuel and weapons permit. When the mission is completed the flights return to their bases [26:25,34].

## A.3 Over-The-Flot Defensive Counter-Air (ODCA)

An ODCA aircraft sits on strip alert and waits for a certain type of mission and size of enemy flight to takeoff. It engages enemy aircraft before it enters friendly air space by penetrating a user-defined distance into enemy territory to attack the aircraft. If the ODCA aircraft takes off and fails to intercept, it is able to begin a user-defined orbit over enemy territory, circling on station and waiting for threats. The user can determine that the aircraft will not orbit and should return to base [26:26].

ODCA is similar to DCA missions in that they are both reactive missions. The only difference is the ODCA attempts to engage enemy flights before they enter friendly airspace. This concept was designed for very fast, long range, survivable interceptors.

## A.4 High Valued Asset Attack (HVAA)

An HVAA aircraft may be triggered when it first goes on alert, when an enemy HVA aircraft first arrives at its orbit, or when an enemy HVA aircraft survives another

HVAA attack. HVA flights are planned to cover a predefined set of orbit points. Flights are assigned to orbit points using a priority system. Air combat avoidance behavior is triggered using a user-defined "safety zone." User inputs defined which enemy missions are deemed threatening. When an HVA aircraft's safety zone is penetrated, the HVA flight goes off-station for a duration determined by a user-input random function. If an HVA flight is destroyed, its orbit point is covered by an alert HVA if one exists. HVA flights return home after their orbit time has elapsed.

There are three events that may trigger an HVAA flight against an HVA type flight. The first event occurs when a HVAA flight comes on alert. The second event occurs when an HVA type flight begins an orbit. The final event occurs when an HVAA flight fails to intercept a HVA flight. When a target HVA flight has been identified as a target, an HVAA flight on alert will build a flight path to the HVA flight's orbit point. The HVAA flight intercept point is the HVA orbit point. If an HVA mission is at its orbit point and is avoiding air combat when it is intercepted by HVAA, then a special attrition methodology is applied. A random draw against the interceptor's probability of detection is used to determine if a successful intercept occurred. If so the number of shots per engagement and air-to-air Pk's are applied directly, bypassing the normal air-to-air engagement logic. In all other air-to-air situations involving HVAs, the normal engagement logic is applied [26:26,40].

## A.5 Air-to-air Escort (AIRESC)

A close escort mission accompanies a strike package over enemy territory. During an engagement, escorts may be attacked by enemy fighters. Escorts may either

split off to engage enemy fighters or stay with the strike aircraft. Air escort aircraft are assigned to flight groups based on the priority for air escort support of the flight group's primary aircraft type. The priority for escort support is based upon several factors such as the type of aircraft priority, mission importance, and depth of penetration into enemy territory for penetrating missions or proximity to the FLOT. The number of air escort aircraft to accompany a flight group is determined by user input. Air escort flights will become attached to the flight group they are supporting. They will engage any enemy interceptor aircraft that pose a threat to the flight group. Air escort aircraft may suffer area air defense attrition but do not accompany the flight group into the terminal phase of a ground attack [26:26,41].

**A.6 Fighter Sweep (FSWP)**

A detached escort fighter mission that provides air-to-air protection for a strike package by preceding it and establishing an orbit over the target. FSWP missions are planned to be executed as a precursor to other air-to-ground missions but are flown regardless whether the ground attack missions were actually launched. They may be attacked by enemy ODCA, BARCAP, and DCA flights. After a FSWP aircraft proceeds to its target at a user-defined altitude, it begins a CAP based on the aircraft type's BARCAP parameters. It orbits for a specified amount of time and uses the same engagement logic as BARCAP. It attempts to engage any enemy aircraft that pass through the patrol area. In addition, it is subject to interception by enemy fighters and engagement by enemy surface-to-air defenses [26:39].

## A.7 Summary

The primary goal of a BARCAP, DCA, ODCA, or HVAA mission is to protect a friendly target. Although destruction of opponent strike or HVA aircraft is ideal, destruction is not the only way to accomplish the mission goal. Merely threatening the opponent may cause him to mission abort. The friendly aircraft have then achieved a 'mission kill' [8:105, 20:331].

# Appendix B: Example of Data Input File "Type"

```
typeairmunt: 12
      AMRAAM
      AIM54
      AIM7M
      AIM9X
      AIM9M
      GUN
      AA9
      AA12
      AA10
      AA11
      APEX
      ATOLL

typeaa: 14
      F15C elt_size: X          %c2: XX
            #config: X
            AA1 bingo: XX
                    X AMRAAM
                    X AIM9X
                    X GUN
      F15E elt_size: X          %c2: XX
            #config: X
            AA1 bingo: XX
                    X AMRAAM
                    X AIM9X
                    X GUN
            AG1 bingo: -X
                    X AMRAAM
                    X AIM9X
                    X GUN
      F15A elt_size: X          %c2: XX
            #config: X
            AA1 bingo: XX
                    X AIM7M
                    X AIM9M
                    X GUN
*
*
*
end
```

# Appendix C: Example of Data Input File "A2A"

```
phases
      3
      VLR
      BVR
      WVR

a2a_tactics
      3
      AVERSE
      MEDIUM
      TOLERANT

a2a_munt_preference_by_phase
      VLR
            AA9
            AIM54
      BVR
            AMRAAM
            AA12
            AIM7M
            AA10
            AA9
            AIM54
            APEX
      WVR
            AA11
            AIM9X
            AIM9M
            AMRAAM
            AIM7M
            AA12
            AA10
            APEX
            ATOLL
            GUN
```

max_tgts/volley_by_typeaa_by_typeairmunt

|        | AMRAAM | AIM54 | AIM7M | AIM9X | AIM9M | GUN | AA9 | AA12 | AA10 | AA11 |
|--------|--------|-------|-------|-------|-------|-----|-----|------|------|------|
| F15C   | X      | X     | X     | X     | X     | X   | X   | X    | X    | X    |
| F15E   | X      | X     | X     | X     | X     | X   | X   | X    | X    | X    |
| F15A   | X      | X     | X     | X     | X     | X   | X   | X    | X    | X    |
| F14C   | X      | X     | X     | X     | X     | X   | X   | X    | X    | X    |
| F16B50 | X      | X     | X     | X     | X     | X   | X   | X    | X    | X    |
| B1     | X      | X     | X     | X     | X     | X   | X   | X    | X    | X    |
| SU27   | X      | X     | X     | X     | X     | X   | X   | X    | X    | X    |
| SU24   | X      | X     | X     | X     | X     | X   | X   | X    | X    | X    |
| MiG31  | X      | X     | X     | X     | X     | X   | X   | X    | X    | X    |
| MiG29  | X      | X     | X     | X     | X     | X   | X   | X    | X    | X    |
| MiG23  | X      | X     | X     | X     | X     | X   | X   | X    | X    | X    |
| MiG21  | X      | X     | X     | X     | X     | X   | X   | X    | X    | X    |

max_wpns/tgt/volley_by_typeaa_by_typeairmunt

| | AMRAAM | AIM54 | AIM7M | AIM9X | AIM9M | GUN | AA9 | AA12 | AA10 | AA11 |
|---|---|---|---|---|---|---|---|---|---|---|
| F15C | X | X | X | X | X | X | X | X | X | X |
| F15E | X | X | X | X | X | X | X | X | X | X |
| F15A | X | X | X | X | X | X | X | X | X | X |
| F14C | X | X | X | X | X | X | X | X | X | X |
| F16B50 | X | X | X | X | X | X | X | X | X | X |
| B1 | X | X | X | X | X | X | X | X | X | X |
| SU27 | X | X | X | X | X | X | X | X | X | X |
| SU24 | X | X | X | X | X | X | X | X | X | X |
| MiG31 | X | X | X | X | X | X | X | X | X | X |
| MiG29 | X | X | X | X | X | X | X | X | X | X |
| MiG23 | X | X | X | X | X | X | X | X | X | X |
| MiG21 | X | X | X | X | X | X | X | X | X | X |

a2a_score_by_typeaa_by_typeairmunt

| | AMRAAM | AIM54 | AIM7M | AIM9X | AIM9M | GUN | AA9 | AA12 | AA10 | AA11 |
|---|---|---|---|---|---|---|---|---|---|---|
| F15C | X | X | X | X | X | X | X | X | X | X |
| F15E | X | X | X | X | X | X | X | X | X | X |
| F15A | X | X | X | X | X | X | X | X | X | X |
| F14C | X | X | X | X | X | X | X | X | X | X |
| F16B50 | X | X | X | X | X | X | X | X | X | X |
| B1 | X | X | X | X | X | X | X | X | X | X |
| SU27 | X | X | X | X | X | X | X | X | X | X |
| SU24 | X | X | X | X | X | X | X | X | X | X |
| MiG31 | X | X | X | X | X | X | X | X | X | X |
| MiG29 | X | X | X | X | X | X | X | X | X | X |
| MiG23 | X | X | X | X | X | X | X | X | X | X |
| MiG21 | X | X | X | X | X | X | X | X | X | X |

min_perceived_a2a_score_by_typeaa

| | |
|---|---|
| F15C | XX |
| F15E | XX |
| F15A | XX |
| F14C | XX |
| F16B50 | XX |
| B1 | XX |
| SU27 | XX |
| SU24 | XX |
| MiG31 | XX |
| MiG29 | XX |
| MiG23 | XX |
| MiG21 | XX |

a2a_targets
     2
FIGHTER
     F15C F15A F14C SU27 MiG31 MiG29 MiG23 MiG21     end_typeaa
BOMBER
     F15E F16B50 B1 SU24     end_typeaa

```
a2a_shooters
       13
15AMRAAM
       F15C F15E      end_typeaa
       AMRAAM          end_typeairmunt
16AMRAAM
       F16B50          end_typeaa
       AMRAAM          end_typeairmunt
AIM54
       F14C            end_typeaa
       AIM54           end_typeairmunt
AIM7M
       F15A            end_typeaa
       AIM7M           end_typeairmunt
AIM9X
       F15C F14C F15E F16B50    end_typeaa
       AIM9X                     end_typeairmunt
AIM9M
       F15A F16B50 end_typeaa
       AIM9M           end_typeairmunt
GUN
       F15C F14C F15E F15A F16B50 REDMAX SU27 SU24 MiG31 MiG29 MiG23
MiG21 end_typeaa

AA9
       MiG31           end_typeaa
       AA9             end_typeairmunt
AA12
       SU27            end_typeaa
       AA12            end_typeairmunt
AA10
       MiG29           end_typeaa
       AA10            end_typeairmunt
AA11
       SU27 SU24 MiG31 MiG29 MiG23     end_typeaa
       AA11                            end_typeairmunt
APEX
       MiG23           end_typeaa
       APEX            end_typeairmunt
ATOLL
       MiG21           end_typeaa
       ATOLL           end_typeairmunt


pwe_by_phase,a2a_shooter,a2a_target,shooter_tactics,target_tactics
VLR
AIM54          FIGHTER
{      AVERSE          AVERSE          XX
       AVERSE          MEDIUM          XX
       AVERSE          TOLERANT        XX
       MEDIUM          AVERSE          XX
       MEDIUM          MEDIUM          XX
```

```
             MEDIUM              TOLERANT          XX
             TOLERANT            AVERSE            XX
             TOLERANT            MEDIUM            XX
             TOLERANT            TOLERANT          XX        }
AIM54 BOMBER
{            AVERSE              ALL               XX
             MEDIUM              ALL               XX
             TOLERANT    ALL                       XX        }
AIM54        MAX
{            AVERSE              ALL               XX
             MEDIUM              ALL               XX
             TOLERANT            ALL               XX        }
AA9          FIGHTER
{            AVERSE              AVERSE            XX
             AVERSE              MEDIUM            XX
             AVERSE              TOLERANT          XX
             MEDIUM              AVERSE            XX
             MEDIUM              MEDIUM            XX
             MEDIUM              TOLERANT          XX
             TOLERANT            AVERSE            XX
             TOLERANT            MEDIUM            XX
             TOLERANT            TOLERANT          XX        }
AA9          BOMBER
{            AVERSE              ALL               XX
             MEDIUM              ALL               XX
             TOLERANT            ALL               XX        }
AA9          MAX
{            AVERSE              ALL               XX
             MEDIUM              ALL               XX
             TOLERANT            ALL               XX        }
end_phase

BVR
AIM54        FIGHTER
{            AVERSE              AVERSE            XX
             AVERSE              MEDIUM            XX
             AVERSE              TOLERANT          XX
             MEDIUM              AVERSE            XX
             MEDIUM              MEDIUM            XX
             MEDIUM              TOLERANT          XX
             TOLERANT            AVERSE            XX
             TOLERANT            MEDIUM            XX
             TOLERANT            TOLERANT          XX        }
AIM54 BOMBER
{            AVERSE              ALL               XX
             MEDIUM              ALL               XX
             TOLERANT            ALL               XX        }
AIM54        MAX
{            AVERSE              ALL               XX
             MEDIUM              ALL               XX
             TOLERANT            ALL               XX        }

15AMRAAM     FIGHTER
{            AVERSE              AVERSE            XX
             AVERSE              MEDIUM            XX
```

107

```
        AVERSE          TOLERANT        XX
        MEDIUM          AVERSE          XX
        MEDIUM          MEDIUM          XX
        MEDIUM          TOLERANT        XX
        TOLERANT        AVERSE          XX
        TOLERANT        MEDIUM          XX
        TOLERANT        TOLERANT        XX      }
15AMRAAM    BOMBER
{       AVERSE          ALL             XX
        MEDIUM          ALL             XX
        TOLERANT        ALL             XX      }
16AMRAAM    FIGHTER
{       AVERSE          AVERSE          XX
        AVERSE          MEDIUM          XX
        AVERSE          TOLERANT        XX
        MEDIUM          AVERSE          XX
        MEDIUM          MEDIUM          XX
        MEDIUM          TOLERANT        XX
        TOLERANT        AVERSE          XX
        TOLERANT        MEDIUM          XX
        TOLERANT        TOLERANT        XX      }
16AMRAAM    BOMBER
{       AVERSE          ALL             XX
        MEDIUM          ALL             XX
        TOLERANT        ALL             XX      }
*
*
*
end_phase

WVR
15AMRAAM    FIGHTER
{       AVERSE          AVERSE          XX
        AVERSE          MEDIUM          XX
        AVERSE          TOLERANT        XX
        MEDIUM          AVERSE          XX
        MEDIUM          MEDIUM          XX
        MEDIUM          TOLERANT        XX
        TOLERANT        AVERSE          XX
        TOLERANT        MEDIUM          XX
        TOLERANT        TOLERANT        XX      }
15AMRAAM    BOMBER
{       AVERSE          ALL             XX
        MEDIUM          ALL             XX
        TOLERANT        ALL             XX      }
15AMRAAM    MAX
{       AVERSE          ALL             XX
        MEDIUM          ALL             XX
        TOLERANT        ALL             XX      }
16AMRAAM    FIGHTER
{       AVERSE          AVERSE          XX
        AVERSE          MEDIUM          XX
        AVERSE          TOLERANT        XX
*
*
```

```
*
AIM9X          FIGHTER
{      ALL                   ALL                     XX      }
AIM9X          BOMBER
{      ALL                   ALL                     XX      }
AIM9M          FIGHTER
{      ALL                   ALL                     XX      }
AIM9M          BOMBER
{      ALL                   ALL                     XX      }
GUN            FIGHTER
{      ALL                   ALL                     XX      }
GUN            BOMBER
{      ALL             ALL                           XX      }
*
*
*
End_phase


max_volleys(min,mode,max)_by_phase,a2a_shooter,a2a_tgt,shooter_tactics

VLR


AIM54          FIGHTER
{      AVERSE            XX    XX    XX
       MEDIUM            XX    XX    XX
       TOLERANT          XX    XX   XX }
AIM54          BOMBER
{      ALL               XX    XX   XX }
*
*
*
end_phase


BVR

*
*
*
prob_unanswered_volley_by_phase,a2a_shooter,a2a_shooter,shooter_tactics

VLR

AIM54       AA9
{      ALL             XX      }
AIM54       AIM54
{      ALL             XX      }

AA9         AIM54
{      ALL             XX      }
AA9         AA9
{      ALL             XX      }
end_phase
```

```
BVR

15AMRAAM    AA9
{      AVERSE            XX
       MEDIUM            XX
       TOLERANT          XX     }
15AMRAAM    AA12
{      AVERSE            XX
       MEDIUM            XX
       TOLERANT          XX     }
15AMRAAM    AA10
{      AVERSE            XX
       MEDIUM            XX
       TOLERANT          XX     }
15AMRAAM    APEX
{      AVERSE            XX
       MEDIUM            XX
       TOLERANT          XX     }

end
```

# Appendix D: Example of Data Input File "Escape"

```
a2a_escape_classes
        3
4GEN
        F15C F15A F14C SU27 MiG31 MiG29 F15E F16B50 end_typeaa
3GEN
        MiG23 MiG21 end_typeaa
BOMBER
        B1 SU24 end_typeaa


escapeDat(lowFR,Pesc,hiFR,hiPesc,bias)by_phase,a2a_escape_class,a2a_esc
ape_class
@bias of -1.0 means all escape opportunities come before first volley
@bias of 0.0 means escape opportunities equally distributed amongst
volleys
@bias of 1.0 means all escape opportunities come after last volley

VLR
        4GEN
                4GEN    XX   XX        XX XX        XX
                3GEN    XX   XX        XX XX        XX     -X
                BOMBER XX    XX        XX XX        XX     -X
        3GEN
                4GEN    XX   XX        XX XX        XX     -X
                3GEN    XX   XX        XX XX        XX     -X
                BOMBER XX    XX        XX XX        XX     -X
        BOMBER
                4GEN    XX   XX        XX XX        XX     .X
                3GEN    XX   XX        XX XX        XX     .X
                BOMBER XX    XX        XX XX        XX     .X
 BVR
        4GEN
                5GEN    XX   XX        XX XX        XX     .X
                4GEN    XX   XX        XX XX        XX     .X
                3GEN    XX   XX        XX XX        XX     .X
                BOMBER XX    XX        XX XX        XX     .X

*
*  -
*

a2a_escape_desire_classes
        3
FIGHTER
        F15C F15A F14C SU27 MiG31 MiG29 MiG23 MiG21 end_typeaa
MULTI
        F15E F16B50 end_typeaa
BOMBER
        B1 SU24 end_typeaa
```

```
escapeDesireDat(FRthreshold)by_phase,a2a_escape_desire_class,a2a_tactic
s

VLR
        FIGHTER
                AVERSE          XX
                MEDIUM          XX
                TOLERANT        XX
        MULTI
                AVERSE          XX
                MEDIUM          XX
                TOLERANT        XX
        BOMBER
                AVERSE          XX
                MEDIUM          XX
                TOLERANT        XX
BVR
        FIGHTER
                AVERSE          XX
                MEDIUM          XX
                TOLERANT        XX
        MULTI
                AVERSE          XX
                MEDIUM          XX
                TOLERANT        XX
        BOMBER
                AVERSE          XX
                MEDIUM          XX
                TOLERANT        XX
WVR
        FIGHTER
                AVERSE          XX
                MEDIUM          XX
                TOLERANT        XX
        MULTI
                AVERSE          XX
                MEDIUM          XX
                TOLERANT        XX
        BOMBER
                AVERSE          XX
                MEDIUM          XX
                TOLERANT        XX

end
```

## Vita

Capt David Pugh was born on 8 August 1972 in Memphis, TN. He graduated from Evangelical Christian School in 1990. In May, 1995 he graduated from Texas A&M University with a Bachelor of Science in Industrial Engineering and was commissioned through the Air Force ROTC program and Texas A&M's Corps of Cadets. He arrived at his first assignment at Tinker AFB, OK and held a position as a Manpower and Quality Officer. In August 1998, he entered the School of Engineering, Air Force Institute of Technology. Upon graduation, he will be assigned to the Air Education and Training Command Studies and Analysis Office at Randolph AFB, TX.